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THE INSTITUTE OF PETROLEUM

AN Ordinary General Meeting of the Institute of Petroleum was held at 26 Portland Place, London, W.1, on 6 November 1957, the Chair being taken by Dr E. B. Evans, a vice-president of the Institute.

The General Secretary read the minutes of the previous meeting, which were confirmed and signed as a correct record. He also announced the names of members elected since the previous meeting.

The Chairman, introducing the authors of the paper to be presented, said: One of the most difficult problems which both the refiner and the marketer have to face is the estimation of how much petroleum and its various products will be required annually during the next few years. One aspect of this very difficult problem will be discussed by our authors to-night.

Both Mr Chandler and Mr Lindsell are experienced economists who are very well fitted to discuss this intricate matter. Mr Chandler, who has had a very wide experience, previously served on the *Financial Times* and is now manager of the Economic Division of the Trade Relations Department of the Shell Petroleum Company. Mr Lindsell has also been with the Shell Petroleum Company for a number of years and is now manager of the Industry and Group Analysis Division of the Trade Relations Department.

CYCLICAL FLUCTUATIONS AND BLACK OIL DEMAND—AN INTRODUCTION*

By G. CHANDLER† (Member) and D. A. LINDSELL†

INTRODUCTION

THE significance of cyclical fluctuations for future long range planning in the oil industry is obvious. The scale and direction of its investment projects and their anticipated profitability clearly necessitate as full a study of future economic developments as possible. Moreover, economic fluctuations have additional significance as the darkening of the main product stream brings the relationship between product demand and industrial activity into closer alignment. The intention of this paper is to consider the impact of these fluctuations on black oil demand.

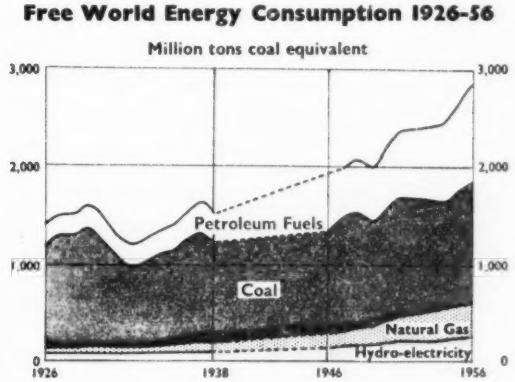

FIG 1

Since there are few factors, either political or economic, that are not relevant to such a study, it is inevitable that our knowledge is incomplete and that much of this paper, in particular where it deals with the future, must consist of inference and speculation. The aim therefore is to pose certain questions, to provide certain data, and to sketch a broad impression rather than a detailed analysis.

THE ENERGY PERSPECTIVE

Before turning to the historical background of economic fluctuations themselves it may be helpful to provide some perspective of the problem by showing the proportions of world demand which were supplied by the various sources of energy in the pre-war and post-war periods (Fig 1).

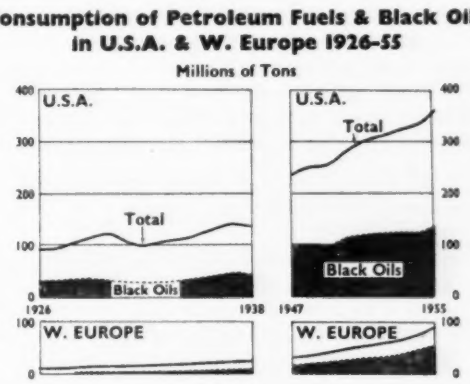

FIG 2

It may also be useful at this point to show the trends of total petroleum fuels and black oil consumption over the same period (Fig 2).

* MS received 16 September 1957.

† The Shell Petroleum Co. Ltd.

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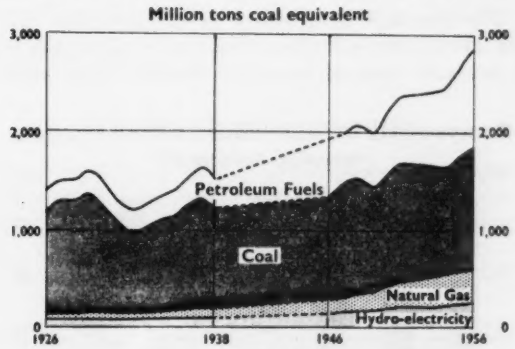
Free World Energy Consumption 1926-56



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Consumption of Petroleum Fuels & Black Oils in U.S.A. & W. Europe 1926-55

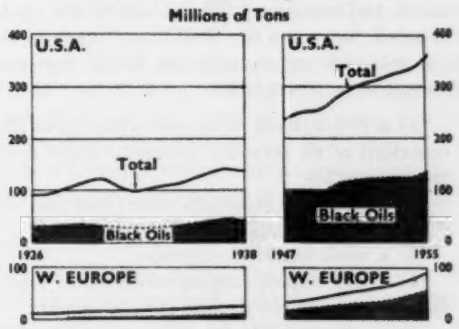

FIG 2

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ECONOMIC FLUCTUATIONS

The Historical Experience

The period following world war I was marked by one acute depression and several of lesser degree. For the purpose of this paper it is intended to examine the great depression of the 1930s and the two U.S. post-war recessions of 1948–49 and 1953–54. These have been sufficiently often discussed to require only a brief résumé here of the factors which have relevance for this study.

Pre-war

The depression of the 1930s was characterized by its length and severity: Free World industrial production reached a peak in 1929 which was not regained

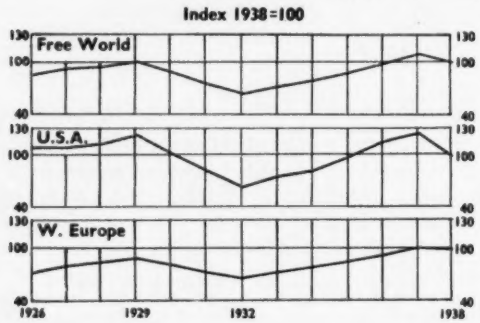


FIG 3

until 1937, and over the period 1929–32 it fell by well over one-third (Fig 3).

The U.S.A.—the world's largest industrial producer and the largest consumer both of energy and primary products—played a dominant role in influencing the rest of the world and setting in motion the cycle of depression and recovery. The nature of this cycle is still debated, but when the Wall Street crash came in 1929 it revealed an economy in which five major weaknesses were perceptible:

(1) a distribution of income which gave about one-third of all personal income to 5 per cent of the population;

(2) a corporate structure which had been built into a huge and unsound edifice;

(3) a weak banking structure;

(4) a U.S. export surplus which led to loan defaults and so to the decline of U.S. exports;

(5) inadequacy of economic intelligence and of courage on the part of the Government to act on the little information that was available.

The swift ebb of confidence, the cessation of investment, which had started to slacken even before the crash, and the application of the wrong remedies added to these weaknesses to make economic disaster certain. Heavy price declines for manufactured goods, for farm products, and raw materials removed any hope of an early recovery, and the downward revision of long-term investment plans brought a pattern of industrial recession, now familiar to historians, in which investment goods suffered most severely. From 1929 to 1932 the U.S. industrial production index fell by just under 50 per cent; but within this total, as the following chart shows, iron and steel, transport equipment, and machinery fell by some 70 per cent (Fig 4).

The U.S.A. at this time absorbed more than one-third of the world's raw materials supplies, and the contraction of American demand rapidly transmitted its influence—both directly through a cut in imports and indirectly through domestic price falls—to the primary producing regions. The resultant fall in prices in turn reduced the level of demand for manufactured goods, and the industrialized regions began to experience unemployment on a scale the memory of which is still a significant factor today. Government action to restore trade balances contributed further to a world-wide contraction of trade and its associated monetary crises. The impact of the U.S. slump on Western Europe was such that a fall in aggregate industrial output of roughly one-quarter occurred between 1929 and 1932. The 1929 peak was not regained until 1935–36.

Post-war

The economic fluctuations experienced since the war have been very different and have taken place in a radically changed economic climate. They have

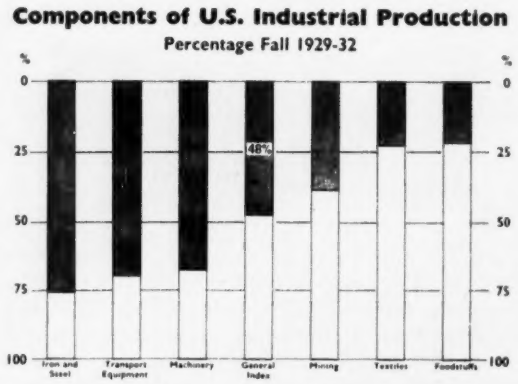


FIG 4

been characterized by relatively slight industrial declines, persisting at most for a period of 1½–2 years, and by a variety of experience in individual countries and individual industries which has prevented any universal recession of the type experienced in the 1930s. A period of reconstruction; a high level of

employment accompanied by considerable increases in productivity; Government and defence expenditure at unprecedented levels; and the economic

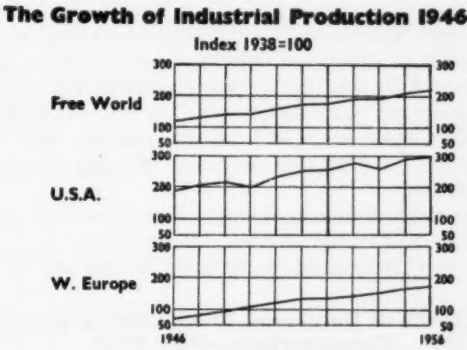


FIG 5

development of primary producing regions have all tended towards excess rather than inadequate demand. None the less, the two chief post-war recessions in the U.S.A. and their repercussions outside have shown that inadequate effective demand generates economic fluctuations whose outline resembles those of the pre-war period, even though their duration and severity have been widely different.

The index of industrial production both for the Free World as a whole and for the O.E.E.C. area shows no absolute fall from 1947 to 1955, despite the experience of individual countries, notably the U.S.A. and the U.K., where distinct falls in industrial output have occurred (Fig 5).

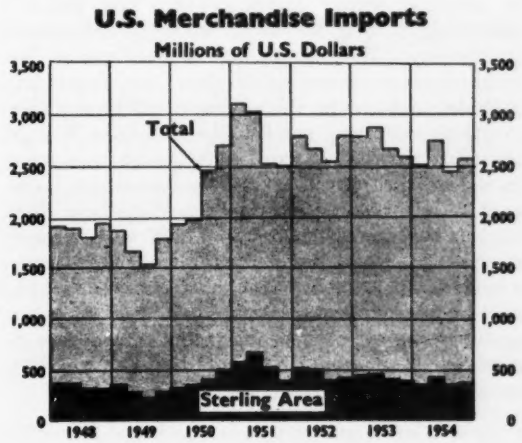


FIG 6

The weaknesses in the U.S. economy which brought disaster in 1929 have been largely remedied in the post-war period. Moreover, while the U.S.A. has continued to dominate the world economy, its domestic industrial fluctuations have not been automatically transmitted to the rest of the world. On the other hand, although the domestic consequences of the 1948–49 recession were mild, the external repercussions were far-reaching, and even the minor pauses experienced in the U.S. economy in 1947 and 1951–52, when manufacturing production fell only slightly but inventory accumulation was sharply reduced, coincided with exchange crises in other countries. The contraction of U.S. imports, illustrated by Fig 6, underlines one of the most important characteristics distinguishing the post-war from the pre-war world economy—the more slender exchange reserves of most countries of the world outside the U.S.A.

Fig 7, illustrating certain indicators of U.S. economic change, emphasizes the relative internal mildness of the recessions.

In both periods industrial production fell by less than 10 per cent (Fig 8), and the most significant change occurred in gross private domestic investment, which was largely accounted for by a substantial fall in

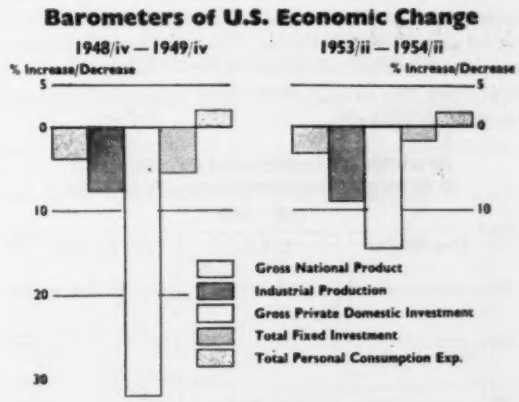


FIG 7

inventories. As would be expected, in both recessions producers' goods were affected more seriously than non-producers' goods. Also in both cases the level of Government expenditure, the buoyancy of total personal consumption expenditure, and—of particular importance—the maintaining of confidence prevented the recession seriously influencing long term investment plans.

However, these "rolling readjustments" as they have been called, in which weakness in one sector of the economy was offset by strength in another, had significant influence abroad. The influence of these movements on U.S. trade with the rest of the world has already been illustrated. The deterioration of trade balances was a major factor in the devaluations of 1949, and even though a large current payments surplus enabled the world to ride out the 1953–54

decline more easily, it has been suggested,* though perhaps too pessimistically, that a fall of 2–3 per cent in employment in the U.S.A. might mean a fall of 15–20 per cent in the value of U.S. imports.

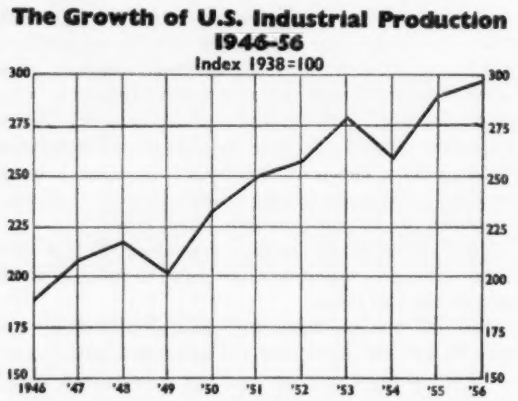


Fig 8

This aspect of post-war recessions is of central importance for the future, both in its possible impact on bunker demand through the contraction of international trade and in the restrictive measures which have been the usual Government weapons to protect their trade balances.

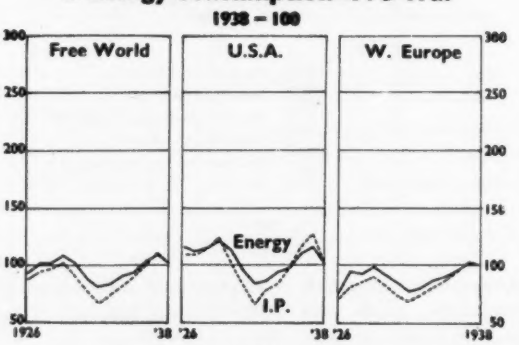


Fig 9

Energy Fluctuations

The fluctuations of industrial production in both the pre-war and post-war periods were followed remarkably closely by energy consumption. This is illustrated in Figs 9 and 10, in which both variables are plotted on an index basis.

The visual picture provided by these diagrams tends to be misleading in that the impression is given that while in the pre-war period energy and I.P. indices remained very much the same, in the post-war period industrial production has increased more swiftly than energy. On closer examination, however, it becomes clear that the basic difference between the two charts is that in the pre-war period overall growth in both variables was very slight, whereas in the post-war years both industrial output and energy have risen rapidly.

In both these periods the elasticity of energy consumption in relation to industrial production in the free world, though not constant, has fluctuated within the relatively small margin of 0·7 to 0·8. This relationship, however, is of little practical use since it comprises an aggregate of widely differing national economies.

For the U.S.A. and Western Europe, the pre-war elasticities of energy in relation to industrial production were determined statistically as 0·56 and 0·80

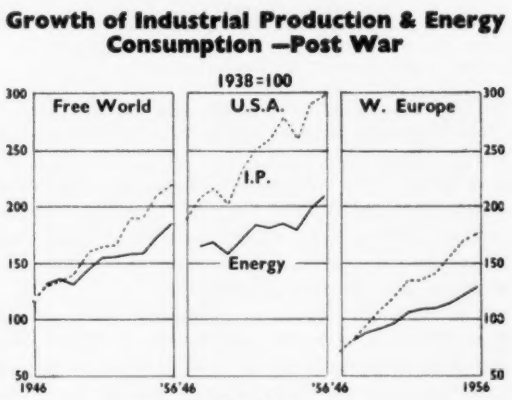


Fig 10

respectively. These elasticities have been assessed to be accurate within about ±0·05. The post-war elasticities for these two areas cannot be determined so precisely. Whereas in the pre-war period the violent fluctuations around the time trend enable firm estimates to be made, the relatively stable economic growth since the war, particularly in Western Europe, has caused the variation around the trend to be much smaller and consequently makes the elasticity measurement less accurate. These elasticities have been calculated as 0·60 and 0·52 for the U.S.A. and Western Europe respectively, but while this brief examination is sufficient to establish that a relationship between the two variables exists over time, further analysis is needed to ascertain the significance of the changes indicated and the extent to which the relationship itself has changed in the years 1946–1956.

THE IMPACT ON BLACK OILS DEMAND

The preceding sections have outlined the nature of economic fluctuations over the past three decades or so, and have summarized some of their characteristics.

* *The World Dollar Problem*, Sir Donald MacDougall.

It has been seen that fluctuations in total inland energy consumption have in the past been associated within relatively small limits with those of industrial production. The next stage consists of an investigation whether black oils consumption has likewise tended to follow past fluctuations in industrial production.

Before outlining the relationship of black oils with industrial production in the U.S.A. and Western Europe from the middle 1920s it is useful first of all to examine Fig 11, which shows that inland black oils consumption in the Free World up to the beginning of the first world war was increasing at an average of some 20 per cent per annum, a rate far in excess of any that could be attributed simply to increasing industrial production. This is, indeed, a clear example—not without significance for the future—of a young industry in the early days of rapid growth to adult status—a growth which is still continuing and which has gone on throughout the entire period we are discussing, thereby changing the relative weight of coal and oil in the supply of total energy needs.

Free World Black Oils Consumption 1900-56

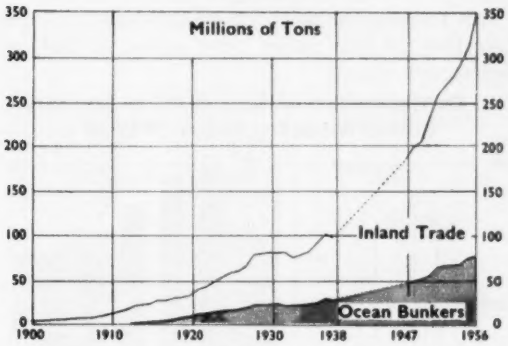


Fig 11

Coal, Black Oil Consumption & Industrial Production 1926-38

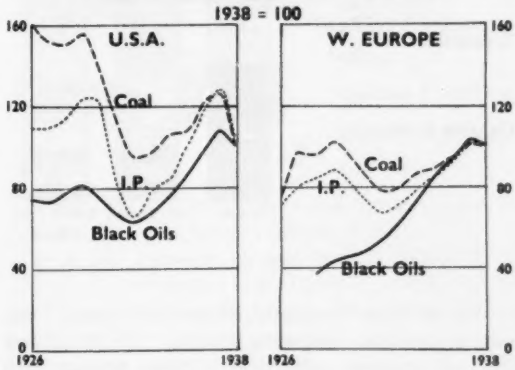


Fig 12

Figs 12 and 13 illustrate the relationship between variations in the level of industrial production, coal and black oils consumption from 1926 to 1956 in the U.S.A. and Western Europe.

U.S.A.

It will be observed that total coal consumption fell by nearly 40 per cent in the depths of the great depression, a far steeper fall than that of black oils demand, which nevertheless was of the order of 25 per cent. By the outbreak of the second world war, however, black oils consumption had fully recovered from this set-back and was running at a level considerably higher than that of 1929, although it followed the downward trend in industrial activity between 1937 and 1938. On the other hand, coal consumption only gradually improved from the 1932 level and, particularly after the downturn of 1938, was still substantially below its 1929 level.

Coal, Black Oil Consumption & Industrial Production 1946-56

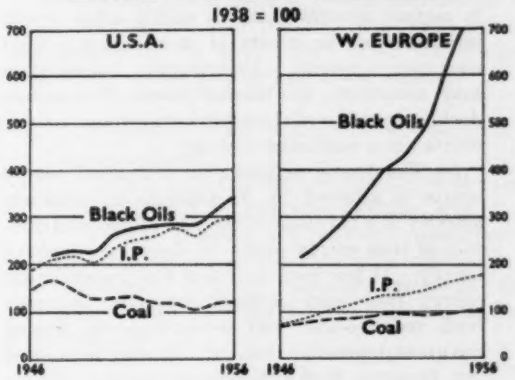


Fig 13

The expansion in post-war black oils consumption in the U.S.A. was clearly affected by the 1948–49 and 1953–54 declines in business activity.

Western Europe

In Western Europe, where the preponderant position of coal in the total energy supply was even more marked than in the U.S.A., the trough in industrial production during the great depression was less than in the U.S.A. in terms of percentage fall 1929–32. Coal consumption followed the decline, but by 1937 had regained its pre-crisis level. Even during the depression, however, black oils consumption registered no absolute decline, although its growth rate was slowed down, and this suggests that the effects of the

disturbance were felt. By 1938 the pre-crisis demand for black oils had more than doubled, whereas industrial production had shown only moderate increase.

The post-war growth in coal consumption has been less than that in black oils, although a slight check in the European economy between 1951 and 1952 resulted in a noticeable slackening in the growth rate of black oils consumption.

At this stage certain aspects suggest themselves which require careful consideration in any study of the relationship between economic fluctuations and black oils demand:

(*a*) The choice of appropriate indices of economic activity, both as a measure of past events and as a guide to the likely severity of future variations. In the foregoing pages the chosen indicator has been the index of industrial production. Ideally, however, the indices used should depend on the black oil end-use under consideration.

(*b*) Where two energy sources are interchangeable, *e.g.* coal and oil, the rate at which one is being substituted for the other. There is some evidence in the foregoing pages to suggest that this rate of substitution may be so high as in certain circumstances to nullify what would otherwise be the effects of at any rate a mild economic recession. Alternatively, substitution may accentuate the normal effects of economic decline upon the relationship between two energy sources in a particular end-use.

(*c*) The degree to which an individual energy source is affected by fluctuations in economic activity is a function of the size of the contribution of that energy source to the total supply of energy. It has been seen that the preponderant energy fuel—coal—suffered far more seriously both tonnage-wise and percentage-wise during the great depression than oil. It may be pointed out, however, that although the general proposition will very often be true in terms of tonnage, it may prove less reliable as to percentage.

At the same time it must be emphasized that a full assessment of economic fluctuations and black oils demand can be derived only from an aggregation of individual country studies and not from overall trends for the world or major segments thereof.

THE IMPORTANCE OF END-USE

Point (*c*) is further illustrated by reference to Fig 14, which shows that in electricity generation, whilst oil consumption declined by some 23 per cent in the depth of the great depression, coal consumption (previously twenty-six times greater than oil consumption) fell by 33 per cent compared with the overall declines of 23 per cent for total inland black oil consumption and 40 per cent for total inland coal consumption. In this particular use, therefore, consumption of coal, by far the senior partner, was noticeably less seriously affected percentage-wise by the great depression than was total coal consumption in all uses.

It is therefore evident that a vital consideration in any study of this nature is to survey as fully as

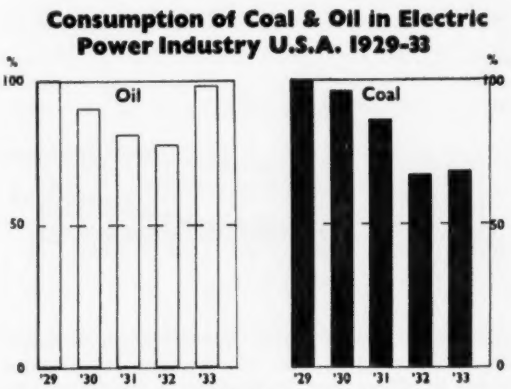


FIG 14

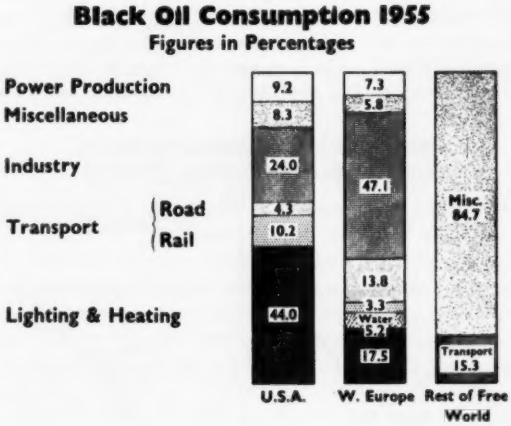


FIG 15

possible at least the main end-uses of energy both from oil and from competing sources. The particular black oils end-use pattern of a given geographical area may render total black oils demand in that area more or less prone to damage by economic disturbances, and it may therefore be of interest to illustrate some patterns from historical data.

Fig 15 gives for 1955 a percentage breakdown of inland black oils demand by end-uses for three major geographical areas of the world—the U.S.A., Western Europe, and the rest of the Free World. The detailed information relates only to the first two areas, but

together these accounted for 75 per cent of total Free World inland black oils consumption.

The first point to note is the heterogeneity of the end-uses of black oils comparing one zone with another, and strikingly illustrated by the comparison between Western Europe and the U.S.A.

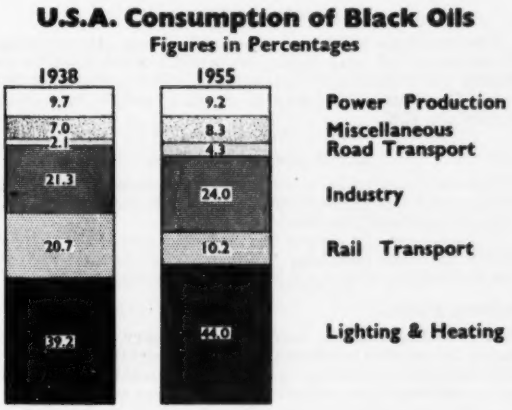


Fig 16

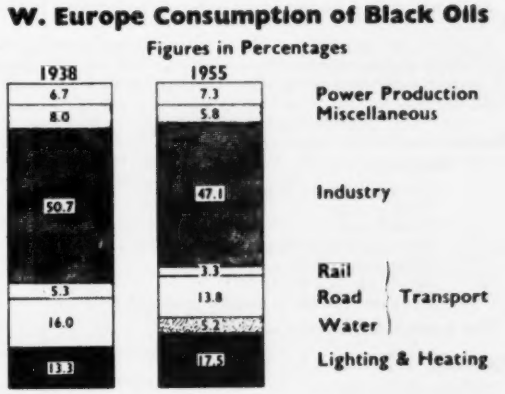


Fig 17

It is also valuable to note in Figs 16 and 17 the change in the relative importance of certain end-uses in the individual zones between the years 1938 and 1955.

THE FUTURE

The Nature of Fluctuations

Post-war experience has left little reason to doubt that economic fluctuations will continue to be part of the pattern of future economic development, although they need not be expected to recur with the apparent periodicity which characterized the eighteenth and nineteenth centuries. While the main characteristics of recessions are likely to remain similar to those of the post-war period, there is no guarantee that their severity may not be greater, although the factors which have prevented any protracted decline in that period can be expected to remain strong in the future.

The greater structural strength of the U.S. economy has already been noted. In the world as a whole there are also several factors, both in the nature of economic growth itself and in the sphere of Government activity, which will tend to cushion future fluctuations. In the first category comes the pressure of underdeveloped areas for economic advancement. In the second category are preparedness on the part of Governments to combat possible recessions, an improvement in the means by which they can do so, and some addition to our knowledge of the tools for predicting the course of the economy.

International commodity agreements, although still not fully tested, may assist in preventing violent price movements which in the past have been a significant factor in accelerating a fluctuation. International co-operation, both between the U.S. and the rest of the Free World and within Western Europe, has helped to provide the means for offsetting economic weaknesses in different sectors of the world economy.

In studying the impact of future fluctuations on black oil demand, therefore, we can make certain assumptions which have some broad justification. The chief of these assumptions are as follows:

(1) that economic fluctuations will continue to be encountered;

(2) that none the less a depression on the scale of the 1930s is not expected to recur; and

(3) that although the post-war experience of fluctuations is expected to provide some guide to the future, it is no necessary guarantee that fluctuations may not be more severe in their intensity.

To these must be added two further and more arbitrary assumptions: first, that any modification of military expenditure in the world will be phased in such a way as to avoid serious economic disruption; secondly, we have discounted for the purpose of this paper the possibility of major economic crises of largely political origin.

Having made these assumptions, there are certain new factors on the scene which must be taken into account in considering the nature and impact of future fluctuations on black oil. The balance of payments aspect has already been mentioned, but it is worth repeating that the precarious state of the monetary reserves of many countries may in a recession provide a further impetus towards the exploitation—possibly uneconomic—of indigenous fuels. The second major factor is the appearance of a new source of energy—nuclear power—which, although limited

in the application at present envisaged for it, has very direct relevance to the subject of this paper.

Their Relationship with Black Oils

It is not possible within the scope of the present paper fully to survey the probable future relationships between black oils demand and economic fluctuations, but it is possible to set out some of the major factors which need to be considered and to suggest one way of obtaining what amounts to an index of vulnerability of black oils demand to changes in the level of economic activity.

The points which seem to call ideally for special study are the following, which must be measured within the context of a detailed industrial pattern:

(*a*) the energy end-use pattern in the particular geographical area and the elasticity of each end-use in relation to economic fluctuations;

(*b*) the relative importance of each end-use in the total demand for energy within the area.

From these two studies one can attempt to determine how important each end-use will be in influencing the extent to which total energy demand will fluctuate in the future and similarly any one of the energy sources being studied.

(*c*) The third essential is an assessment of the degree of substitution which may occur between the various energy sources, *e.g.* oil and coal, within each end-use. Taking a single industry as an example, it is necessary here to consider the elasticity of consumption of each energy fuel in relation to the total energy requirements of that industry, which will involve studying:

(i) the relative degree of efficiency-in-use of each energy fuel in the industry; bearing in mind, first, that substitution is usually a time-consuming operation and is therefore related to the time element in the study of economic fluctuations; secondly, that there may well be a physical limit to the degree of substitution which is practicable;

(ii) political factors, which fundamentally resolve themselves into problems of imported and indigenous fuel.

These considerations include the main elements for study in a comprehensive assessment of the relationships between black oils demand and future economic fluctuations.

In its entirety the calculations involved would be immense for any complex industrialized country, and a basic problem for future research in discussing a whole country's position would be the extent to which the variables can be aggregated.

However, it should be borne in mind that it is not always the country position which needs examination. The extent to which black oils are liable, more or less, to fluctuate as industrial production can be studied in smaller sections of the economy.

Appendix A has been developed to indicate the procedure involved.

APPENDIX A

Assessing the Impact

This Appendix has been developed in order: (1) to express in mathematical form both the variables which need to be studied and their inter-relationships, and (2) to illustrate the use of the mathematical form in regard to certain data available on the U.K.

1. *The Mathematical Form*

The aim of this exercise is to produce a simple model, taking into account the variables affecting each factor separately as well as the overall relationship.

In particular, the crux of the argument should throw light on the following question: "Will black oil demand vary in the future more than total industrial production?"

Relevant Factors

1. It is important to break down industry into as many sectors as possible consistent with the information available. This is so, since each sector will vary considerably with respect to the relationships outlined in the following paragraphs.

2. To each sector we can determine elasticity relating its production to total industrial production. This will quantify the idea that the performance of industries varies in relation to overall business cycles.

3. In each sector we can relate energy requirements to production.

4. Again, in each sector, black oil consumption will be a proportion of total energy requirements. We can determine an elasticity relating black oils consumption to total energy requirements.

Mathematical Relationships

Variables:

Total industrial production	$= P$
Total energy	$= E$
Total black oil	$= B$
Production in industry (i)	$= P_i$
Energy in industry (i)	$= E_i$
Black oils in industry (i)	$= B_i$
Increase in total industrial production	$= \Delta P$

The symbol Δ applies to all increases.

Equations

(1) *Overall Equation:*

$$\frac{\Delta B}{B} = e \cdot \frac{\Delta P}{P}$$

The elasticity (e) is, of course, what we are aiming to determine.

(2) For each industry:

(*a*) $\dfrac{\Delta P_i}{P_i} = a_i \dfrac{\Delta P}{P}$ (Relevant Factor 2)

(*b*) $\dfrac{\Delta E_i}{E_i} = b_i \dfrac{\Delta P_i}{P_i}$ (Relevant Factor 3)

(*c*) $\dfrac{\Delta B_i}{B_i} = c_i \dfrac{\Delta E_i}{E_i}$ (Relevant Factor 4)

(3) Now,

$$\frac{\Delta B_i}{B_i} = c_i \frac{\Delta E_i}{E_i} \quad \text{from (2) (c)}$$

$$= c_i \cdot b_i \frac{\Delta P_i}{P_i} \quad \text{from (2) (b)}$$

$$= c_i \cdot b_i \cdot a_i \frac{\Delta P}{P} \quad \text{from (2) (a)}$$

(4) Suppose (d_i) is the proportion of black oil demand in industry (i),

then $$d_i = \frac{B_i}{B}$$

(5) Now, $$\frac{\Delta B}{B} = \frac{\sum \Delta B_i}{B}$$

$$= \sum \frac{\Delta B_i}{B}$$

$$= \sum \frac{B_i}{B} \cdot \frac{\Delta B_i}{B_i}$$

$$= \sum d_i \cdot \frac{\Delta B_i}{B_i} \quad \text{from (4)}$$

(6) Then,

$$\frac{\Delta B}{B} = \sum d_i \cdot c_i \cdot b_i \cdot a_i \cdot \frac{\Delta P}{P} \quad \text{from (3)}$$

$$= \frac{\Delta P}{P} \sum d_i \cdot c_i \cdot b_i \cdot a_i$$

Therefore,

$$e = \sum d_i \cdot c_i \cdot b_i \cdot a_i \quad \text{from (1)}$$

We have now broken down the elasticity (e) into three component parts, (c_i, b_i, a_i) for each industry (d_i is merely a weighting factor).

2. The Illustration

This particular approach is applied in the following paragraphs to data covering four of the major industries in the U.K.—steel, chemicals, gas, and textiles. The original data covered only the post-war period and does not reflect any extensive cyclical fluctuation. The elasticities have been but broadly estimated without applying refined statistical methods, purely to provide one illustration from which certain broad conclusions may be drawn.

		Steel	Chemicals	Gas	Textiles	All industry
Elasticities:	(i) B with $E = e_i$	2	1·7	2·5	3·3	3·4
	(ii) E with $P = b_i$	1	1·2	1	0·6	0·5
	(iii) P with TOTAL I.P. = a_i	0·5	1·5	0·65	5·5	1
	(iv) B with TOTAL I.P.	1	3	1·8	7	1·7
B as a proportion of TOTAL $B = d_i$, %		35	6	18	6	100
P as a proportion of TOTAL P, %		4·6	4·7	1·4	13·3	100
ENERGY INTENSITY INDEX *		4·5	0·9	15	0·4	1·0
RATE OF INCREASE IN PRODUCTION, p.a.		4	8	1·5	0·1	4·5
B as a porportion of E:						
1948, %		6·0	4·2	2·6	3·4	3·0
1954, %		9·3	5·5	2·6	4·5	4·4

* This index shows the importance of fuel to each industry's output relative to an overall average index of unity. This was compiled by relating energy input to industrial output for the year 1948.

Small though this table is, it illustrates the type of problem which has to be faced:

(1) The elasticities for the individual industries of B with E can vary very substantially industry by industry.

(2) The weighted average of the elasticities (iv) for the four industries is approximately 2·0. This is in fairly close agreement with the figure for all industries (1·7) for which the growth and variations in the individual factors are illustrated in Fig 18.

(3) However, the reasons for this approximate similarity in elasticities are clearly not the same.

It should be noted that the elasticities calculated above are the average over the given period. In applying the formula to the future the possibility of change in the elasticities will, of course, need to be examined. The final expression for the future is obtained by linking the weighted answer with the change in economic fluctuations as a whole.

Covering the whole field of industry can be an immense job. However, by gradually enlarging the scale of the enquiries our knowledge of the behaviour of black oils in the light of economic fluctuations should be increased, with a consequent help to the operational planning of supply.

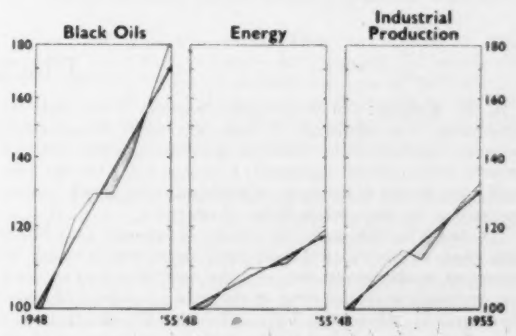


FIG 18

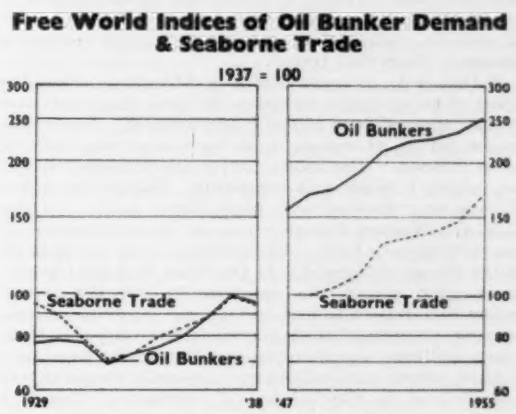


FIG 19

APPENDIX B

Factors Affecting Bunker Demand

The object of this Appendix is to indicate the course of certain variables which influence the rate of growth of bunker demand.

Fig 19 illustrates the severity with which the world levels of seaborne trade and oil bunkers were affected during the 1929–32 depression and the 1937–38 recession. Although it is clear that oil bunker consumption reflected major economic fluctuations, it is difficult to interpret the relationship between the two variables because of the rapid rate of conversion from coal to oil firing which was at work in the 1930s. This rate of conversion is indicated by the fact that the proportion of

the world merchant fleet which was oil-fired grew from one-third in 1925 to more than half of the total fleet by 1938.

In the post-war period the volume of seaborne trade and the demand for oil bunkers have both grown at a rapid rate. Between 1948 and 1955 world oil bunker consumption has expanded by an annual rate of increase of some 6 per cent. The seaborne quantum has grown at a rate of more than 7 per cent, annual average increase.

The consequences of conversion from coal to oil firing have been such that less than 10 million tons of coal a year are now consumed as Free World ocean bunkers, compared with a figure of 74 million tons of oil bunkers in the Free World in 1955.

Changes in the future level and pattern of world seaborne trade will react on the level of demand for oil bunkers in two ways:

(*a*) via changes in the volume and pattern of dry cargo trade; and

(*b*) via—

(i) growth in the level of inland oil consumption itself.

(ii) changes in the pattern of inland oil consumption itself.

An assessment of the relationship between fluctuations in the volume of world seaborne trade and fluctuations of oil bunker demand may be expected to require separate consideration of the factors involved in (*a*) and in (*b*).

DISCUSSION

A. E. Makins: It is possibly because I am not an economist, but although I can see some relationship between economic fluctuations and the general rate of growth in industrial demands, I cannot see how one can really try to tie it down to the demand for black oils in particular, or any other form of energy.

I noticed in the authors' indices on energy and black oils, that in about 1951 and 1952 there was a check or recession in the economic growths, and that tied in very conveniently with the drop in the rate of growth of black oil demand. However, I thought that the check in the rate of growth was due to the increase in price of black oils. Between January 1951 and January 1952, there were something like four increases in the price of black oils, equivalent to about 25 per cent increase, and I think it was those price increases which really checked the rate of growth, rather than the general slight economic recession about that period.

If that is so, it looks as if it is difficult to assess the effect of an economic recession on black oils, even after it has happened, and to really apportion it. To do that in the future, therefore, must become correspondingly more difficult. The other matter the authors touched on, which I think will completely obscure the effect of economic fluctuations, particularly as far as the U.K. and Western Europe is concerned, is the maximum use of indigenous fuels. Mr Maudling made a statement in the House of Commons to the effect that the Government must accept the responsibility for the overall policy with regard to fuel and it must intervene, stimulate, and encourage where necessary, to ensure that there was a sufficient supply of energy, but at the same time it must ensure that indigenous fuels make the maximum contribution to the balance of payments. This is a problem which the U.K. will have for some time.

The authors also touched on the question of nuclear power. I think that this has a far greater bearing on the demand for black oil than these economic fluctuations.

In the U.S.A. another effect is that industry, to a much greater extent than in the U.K., is equipped to switch from one type of fuel to another, virtually at a moment's notice, in order to take advantage of any price concessions, which either coal, oil, or natural gas are prepared to grant. I feel that it is a possible development that industry will equip itself to do so in the U.K. In that event, I would like the authors' opinion on the possibility of the Government really intervening to maximize the use of indigenous fuels at the expense of imported fuels. In other words, throwing the whole of the flexibility of the U.K. energy programme back on to black oils. What would be the effect of that on industry?

D. A. Lindsell: In regard to the first question, we have, of course, looked at the position very broadly, but it is evident in Western Europe that not only has there been a very rapid increase in the consumption of black oils since the war, but also there was a marked slowing down in this rate of increase in 1952 in sympathy with a similar slowing down in industrial production.

Coal consumption over the same period has, in comparison, hardly changed at all. Though in sympathy with those in industrial production, these changes have been minor compared with those in black oils.

In regard to the question of future levels of demand, I should perhaps make it quite clear what we have been trying to do in this paper. We are not really discussing in any detail the average annual rate of growth of an individual energy source over a period of years. What we have discussed is the extent and nature of variations about that trend.

One of the problems with which we are faced in the future is the extent to which, in a given economic climate, indigenous sources of energy will be preferred to imported ones. In this respect, the point Mr Makins made about the U.S.A. as to how quickly one can switch from sources of energy is clearly very important. The problem will, however, vary: if one can only switch over at the end of six months, then one has one type of problem; if one can change in a very much shorter period, as in the U.S.A., then one has another.

It is gratifying that Mr Makins mentioned these things, because they are obviously the aspects on which one has to make up one's mind in studying the relationship of what we call " B. with E." in the future.

G. Chandler: I had hoped that we had included every factor which might affect the demand for black oils, *i.e.* substitutability (which, of course, includes price), the place of nuclear energy, and the balance of payments question to such an extent that we would be protected against any form of question whatsoever by taking refuge in the complexity of the problem!

Having said that, I feel that Mr Makins' question sprang from looking chiefly at the U.K.; as Mr Lindsell has already said, many of these indices were very much broader than the U.K. The smallest unit we used was the U.S.A. or Western Europe.

We would question to some extent the statement in the House of Commons. It was interesting that Mr Maudling's indices of industrial growth for the U.K. added up very neatly to doubling our standard of living in 25 years. At that particular time it was still a useful political handle, and Mr Maudling was, I think, grasping it. We would disagree with his figures in that we think

he was tending to underestimate the rate of industrial advance and therefore the energy demand that goes with it.

We put nuclear power in as a factor, but did not evaluate it.

The point about the exploitation of indigenous fuels in any country is a very difficult and delicate one, partly because the oil industry is obviously an interested party. Nonetheless, I think one can examine this question perfectly objectively. The U.K. economy, looked at from the point of view of economic philosophy, has developed on imports and exports, and I think that if we try to be autarkic, self-sufficient in any particular line, this would be a mistake, although it must be recognized that energy is a highly strategic factor in our economy. There are very substantial limits, though, to the extent to which one can develop indigenous resources. The coal industry has had money poured into it since the war, and the results have not measured up to the hopes. Estimates of the future vary very much. The coal industry has one estimate for itself, we probably have another, and probably someone else has a third. Past failures are, however, perhaps some guide to the future. Nuclear power, in its present application, is only going to generate electricity. Again, we have to examine end use. Can we simply turn to electricity in all the end uses for which black oil and petroleum products as a whole are now used? I consider the answer is certainly no. Secondly, merely to cut down imports and make fuel costs rocket upwards is really the worst form of economy. As I mentioned, the U.K. is an importing and exporting nation. Unless atomic energy is run on quite a high load factor it is going to become quite uneconomic and industry will have to pay very much more for its energy. Therefore, there is only a certain percentage of energy demand that can be met by nuclear energy.

H. E. Barry: I found the appendix much the most interesting part of the paper. I thought that the concept of an energy intensity index was a most interesting one, but was rather puzzled as to how it was to be calculated. What was the common unit? Was it money value, or was it some other factor? According to the footnote, the calculation relates to 1948, and I imagine that if one is going to obtain a fairly exact valuation, one has to have figures from the Census of Production in order to get at the problem. I wonder whether the fact that the results of the Census are so long delayed is going to affect this concept of using an energy intensity index in an up-to-date form?

D. A. Lindsell: In order to calculate the energy intensity index, the following information is required.

For each industry for a given year, the total fuel consumption and net output are required.

In certain industries, such as the fuel industries and steel, it is important to take the net fuel consumption, making allowances for sales of fuel to other industries.

For any year, it is relatively simple to determine the fuel consumption in an industry in terms of coal equivalent. The relative outputs of various industries for any particular year are more difficult to estimate. For this reason, it was decided to use the year 1948, for which a census of production existed.

It is possible to use the increases in output of the various sectors for the U.K., since these are all quoted in the *Monthly Digest of Statistics*. For example, the relative outputs for the various industries in 1950 could be obtained by using the weights determined from the Census of Production in 1948 and the percentage increases for each sector between 1948 and 1950.

Steps in the Method

(1) Determine for each industry a ratio of fuel consumption to output (r). The actual unit does not matter so long as it is the same for each industry.

(2) Determine the total fuel consumption for all industry and the total output for all industry.

(3) From the above, determine the fuel to output ratio for all industry (R).

(4) Determine $\frac{r}{R}$ for each industry. These are the energy intensity indices as determined for this paper.

This derived index shows how important to each industry is its fuel supply. An industry for which the index equals 1·0 uses an average amount of fuel relative to its output. An industry where the index is 0·5 uses only half as much fuel as an average industry, while an industry with an index of 2·0 uses twice as much.

G. V. Davies: I would like to join issue with the authors in regard to the importance of nuclear energy. I think they have underestimated this because we have been told by the UKAEA that in a few years' time, the curves will cross, and the cost of electric power generated by nuclear energy will be less than that generated by conventional stations. In any case, in all countries there is a big base load for which nuclear power stations are quite suitable. I think also that there are a number of subsidiary factors operating in Europe which are not disclosed in the paper, particularly in the OEEC countries. Many of these imported coal from Great Britain, Germany, Poland, and other European countries, supplies which are no longer available to them, either for political reasons or because the countries no longer have any to export. In consequence, they are importing American coal, which is extremely expensive, and it costs dollars, which are even more scarce. Thus, they have turned over very rapidly to black oil.

Another factor, too, is that there are so few pipelines in Europe that vast quantities of crude oil and finished products are being moved by road tanker. I believe there is one place where something like 5 million tons of oil a year is being moved by road inland from the coast, a distance of over 100 miles. All these tankers are running on diesel oil, and so are most heavy vehicles in Europe to-day. So that the ratio of diesel fuel to petrol consumed on the Continent is far greater than in the U.S.A., and the number of diesel-driven vehicles seems to be increasing every year. In fact, Germany is turning over quite rapidly to diesel passenger cars as well.

G. Chandler: The last thing I wanted to suggest was that within a reckonable number of years, atomic energy will not become competitive with conventional power stations. It is foolish to pretend to oneself that atomic energy is not going to play a very substantial part in the energy field.

However, even when there are competitive costs between atomic energy and conventional power stations, they are competitive for atomic energy only at a high load factor. There is a substantial base load in the U.K., but it is none the less, under present industrial conditions, a limited one. If atomic energy stations are built up beyond a certain limit they will get beyond the margin of economic operation.

Atomic energy, as envisaged at the moment, will

compete with oil in one only particular outlet, electricity generation, which, looked at the world over, is not a particularly important one for oil in proportion to total petroleum demand or to total black oil demand.

I quite agree with Mr Davies in regard to U.S. imports of coal to Europe. It is obviously a factor which one has to take into consideration because it is related very closely to substitutability. One has to watch the point at which American coal can compete with black oil, which is also being brought in as an import.

G. V. Davies: The effect of the rapid turnover in most European countries from petrol-driven vehicles to the diesel-driven vehicle, including even diesel-driven passenger vehicles in Germany and, to a lesser extent, in France and Italy, is seldom fully appreciated.

I believe the position is now so serious that certain European countries which would like to increase their refining capacity to produce more fuel and diesel oil cannot do so because they do not know what to do with the petrol produced.

D. A. Lindsell: This is an interesting and important problem in the more technical field of refinery operation, linked with the problem of the type of crude which will be available. The problem has not yet reached, in non-technical terms, the point of no return or of being insoluble.

The real point is illustrated by the difference between the U.S.A. and Europe. Whereas, in the U.S.A., there is no real fiscal differential between gasoline and diesel in favour of diesel, and therefore no artificial stimulus to the greater use of diesel engines, there certainly is in Europe. Moreover, it is not only a problem in Europe, but it is also one in many other parts of the world.

R. S. Hopper: Reference has been made to the speech that Mr Maudling made in the summer relating to fuel requirements: one thing that he said was that he estimated the growth of industrial production in the U.K. would rise by 3½ per cent per annum, and the growth of energy demand would rise with it by 2½ per cent per annum. Simple people like myself have come therefore to the conclusion that there is a sort of five-sevenths relationship; for every seven points that industrial production goes up, energy requirements go up by five points. Yet if one looks back to the period from 1952 to 1956, the growth of British industrial production went up, in fact, less than the growth of energy requirements. One is inclined to assume that to produce 7 per cent more goods one requires 5 per cent more fuel. Because of the experiences between 1952 and 1956, there must be other factors which cause an increase in the demand for energy besides increased productivity. The one which comes most readily to mind is the requirement of the average person for greater comforts, which include a better standard of heat in the home besides the use of many electrical domestic appliances. There can also be an increased use of energy in the factory which does not necessarily affect the rate of production; we are continually requiring more energy to take the load off the workers' arms. I would like to ask the authors if they could say why they and Mr Maudling tie this energy requirement so specifically to industrial production, whereas, in fact, it does not appear to have been related in the least.

G. Chandler: I do not think the energy/I.P. association is a very exact indicator. If one takes energy in industry or manufacturing industry (if one can separate it out) one gets a more realistic picture.

Mr Hopper mentioned taking the load off the workers' arms, heating homes, etc. There, I think, is the differentiation. Taking the load off the workers' arms is a direct industrial use; heating the home is a non-industrial use which cannot be related to an index of industrial production. One can find relationships between energy demand and national income, gross national product, and very many things, but it is possible to be misled by them. There are a lot of factors which are directly related, and I would again say that energy/I.P. relationships are difficult to interpret, and they, of course, vary in different countries and different areas. Ideally I absolutely agree with the implications of what Mr Hopper said—one wants to look at energy in industry rather than energy as a whole. In parenthesis I should like to add that we think Mr Maudling's figure of 3½ per cent a little low.

H. E. Barry: It may not be generally realized that in this concept of energy, the consumption of petrol by private cars, of paraffin, of aviation fuel, and of vaporizing oil for tractors are all included in the energy equation. It is thus not only energy in the form of black oils as such which goes into the equation. The consumption of the motor car is converted into tons of coal equivalent. If one takes the index of industrial production *per se*, that does not give the whole answer. The more money there is in people's pockets, the more demand there is for motor cars, for paraffin heaters, and so forth.

G. Chandler: It is a truism to say that oil is bound up with economic development. However, if one looks at any index of economic growth of a country, one will find oil curiously closely associated with it. It is not a nonsensical correlation, although it may be a crude one.

D. A. Lindsell: We have produced a very simple table in Appendix A for the purposes of this paper, but as many lines as one likes can be introduced in order to get the correct relationships. One can, for example, first of all study the relationship of industrial production with national income and then merely work all the way down the line until one thinks one has really understood what is fluctuating with what. In the present instance we have taken a simple illustration over six to seven years. Statistically, the results can be only very approximate. It is the idea rather than the results which is important in this paper.

W. A. Russell: It is most interesting to speculate on the amount of control the oil industry itself might have on this index of production. We have not heard why it stands at its present level, nor the effect of the price of fuel on it. We have heard how, in America, the increase in production has been tremendous, due to the high energy consumption *per capita* stemming from low cost fuels. In other parts of the world energy costs are mostly fairly high, yet it is understood that the basic cost of producing oil is very much lower in the Middle East than in America, owing to the comparatively large oil pools and few wells needed for production. It would thus be interesting to speculate on the future of the U.K. oil industry if prices could be reduced, and also to see what effect that would have on the index of production.

G. Chandler: The oil price structure is an expert's field with which I am not qualified to deal. In general,

however, oil must clearly be competitive to get into the market at all. It has a rapidly growing market, and it has competed with other sources of energy to obtain it. It has obtained it for many reasons, partly through availability, partly through efficiency as a fuel, partly through flexibility, and also of course through price. In this question of substitutability, price is a very substantial factor. To put Mr Russell's question in a different way, if the price of oil is halved to-morrow, will sales be doubled? I am sure the answer is "no." These things change slowly. Moreover, we must examine where and for what reasons oil is used. The steel industry, the metallurgical industries, and ceramics use oil because it gives them something which coal cannot give them; in power stations, where oil has no special advantage other than availability and its higher calorific value, it must compete simply on a price basis. It is competing directly with coal, and will in the future compete with atomic energy.

D. A. Lindsell: It is rather interesting that we have come to this question after the first one, where it was more or less suggested that we might be in a position where we would have less oil demand because of the need to absorb growing indigenous sources of competitive fuels.

W. A. Russell: One of the earlier questioners spoke of the surplus of motor spirit. That is obviously a political factor, not controlled by the industry, because half the price is tax. I presume that in Germany, where diesel fuel is also replacing motor spirit, the position is the same as in the U.K. Where tax is high the relative popularity of the two fuels is controlled by their tax differential.

The position between black oils and coal might be the same. I have no doubt that if the industry was able to reduce the price of its black oils to a level lower than indigenous coal, the fiscal weapon would be used to retain the competitive position of coal.

However, the implication of the question was as much to suggest that in looking at these problems one should look ahead and do some crystal gazing, rather than take one's attitude for the future entirely from the past. This applies also to the attitude to be taken over nuclear energy, because the pattern of energy consumption is bound to change as the relative costs of various kinds of energy change. Thus, in the nuclear age, electric trains will replace steam or diesel and new and more efficient batteries may be developed.

All these features of the future must be considered when building up the forward plan. Forecasts may not be perfect but will show the trends. They must, of course, be revised as the pattern changes.

G. Chandler: We both agree 100 per cent. We like to view the past as an example and then condition it by our own reasoned as well as imaginative thinking in order to come to reasonable conclusions about the future. I have been careful to say that the use of nuclear energy, as envisaged now, is in power stations and is therefore limited as far as present plans go. However, I am absolutely certain we have to think of variations in energy use.

Dr E. B. Evans: As Mr Lindsell has said, nuclear energy will in future be competitive with fuel oil in the power station field. I believe that it is the declared policy of the UKAEA that the rate of installing nuclear power shall be equal to that of the increase in the overall energy demand (J. C. Stewart, OEEC Conference "The Industrial Challenge of Nuclear Energy," April 1957). If this is to be generally so, and bearing in mind that power production in Western Europe accounts only for 7 or 8 per cent of black oil consumption (Fig 15), then nuclear power must make inroads into other sections of the market, *e.g.* into the general industrial field or heating. It is also the case that the National Coal Board has planned to increase production of coal by 25–30 million tons per annum within the next ten years, although whether such high figures will be realized is perhaps another matter. If nuclear power may make some inroads into the black oil demand and increased coal production may also have an effect, does it not make it very difficult to forecast future black oil demands, when the technical picture is changing so rapidly? I know that the situation is very different in the U.S.A., where the economics of nuclear and other forms of power generation are very different, but a similar situation to that which has been suggested for the U.K. might well apply in Western Europe.

G. Chandler: I had not realized that this was the declared objective of the UKAEA—that atomic energy should rise commensurately with the increase in energy demand. I would certainly have thought that present programmes could not meet such an objective and that it would anyhow be unrealistic in practical terms. Atomic energy is entering the market at a time when energy demand as a whole is rising at a very steady and substantial level. It will therefore tend to be complementary, particularly in its initial stages, to the more conventional sources of power. Its effect on black oils, or for that matter on coal, will depend on two things.

First, on the actual nuclear generating capacity which is constructed; secondly, on the extent to which the National Coal Board may be able to fulfil its production plans. Any talk of stabilization in this picture is to my mind unrealistic. The stabilization of fuel imports was discussed in "A Target for Euratom," but the nature of growing energy demand and the size of the present atomic energy plans in Europe both suggest that talk of such stabilization is unrealistic. I feel it a mistake to look at these developments in too rigid terms. If energy is provided, a demand for it is generated, and there is thus a snowballing effect. We may well, in forecasting the future of black oil demand, keep our working margins comparatively wide, but we certainly expect to see oil as a competitive source of energy, and we certainly expect it to compete successfully with these other sources of supply if given the freedom to do so.

Dr E. B. Evans: The particular forecast is a rather startling prediction, but whether it is practicable or not, I do not know.

G. Chandler: Atomic energy is a young industry and an ambitious one. Nevertheless, its plans have to be examined realistically. (In parenthesis I should say that the UKAEA economists are, in this matter, most solid realists.) The demand for energy is expanding at a very considerable rate, and I have no doubt that there is room in an expanding market for all sources of energy.

E. A. E. Nichols-Roth: I would like to ask Mr Chandler whether he can expand on his analysis of cyclical fluctuation in terms of the present world trade recession.

G. Chandler: I was careful to say that we are not predicting the timing of cyclical fluctuations. The evidence is still very short in terms of time to say what has happened to the world economy. American industrial production has admittedly levelled off, but has as yet seen no comparable reflection in Europe. U.S. defence spending is admittedly down, as are various other economic indicators. At the same time there is a celestial economic indicator, the Sputnik, which may have considerable influence in changing the picture as seen at this moment. There is also immense latent strength and astonishing resilience in American economy, as was shown in 1953–54. Government expenditure comprises a substantial proportion of most national products and can clearly wield considerable influence. If I am to make a prediction I would say that we shall see an upturn in the American economy in the third or fourth quarter of 1958, and that before we reach the upturn the decline will not have gone very far.

E. A. E. Nichols-Roth: We have a recession, by any standards that I know, and by any standards which Mr Chandler mentioned, *i.e.* restricted government spending, tight money, and the tanker market, with which I am largely concerned, at an absolute standstill. It was mentioned that the production of petroleum products is still increasing, despite the recession which has occurred. I do not quite see how production can be increasing at a time when we cannot give tanker space away, let alone charter at a profit. I think that the scope of refinery operations might increase slightly, but without an advance in crude and black oil demand, for the moment.

G. Chandler: I am not an expert in this field, but it strikes me that the tanker market is a highly volatile one and by no means a sure indicator of the economic situation. Nor to my mind is it a very sure reflector of a general economic situation. I would agree that there are some of the appearances of a recession in the U.S.A. (although it is worth remembering that this has so far been chiefly confined to the U.S.A.). At the same time, however, I do not think we should be quick to assume that this is heralding any major decline and, as I have already said, this has not gone on sufficiently long for us to be able to look at the situation clearly.

D. A. Lindsell: We should be quite clear on what is happening to the petroleum demand in the U.S.A., since that country has been given particular mention. It is just about bumping along with increase, *i.e.* a little below or a little above, and as far as production is concerned, steps are being taken to bring it into line.

W. A. Russell: Mr Nichols-Roth may have answered his own question on recession, as he did mention the factor of tight money. In both Britain and America there has recently been a definite governmental policy of dear money to curb inflation. The implications of such a policy may be outside the scope of this discussion, but an important effect is a restriction of industrial production. The word " recession " must be taken in this context, since it is part of a deliberate control policy that can be reversed at will by the Government.

S. A. Day: May I revert to the question of forward estimates? I am not quite clear about the meaning of Fig 18. Is it correct to think that the table demonstrates the relationship between the rate of growth of various factors such as energy demand, index of production, etc.?

D. A. Lindsell: The point of the chart is not the rate of growth over a period but the rate of variation around the trend. One can have a slow growth in one factor and a fast growth in another. What we are trying to do is to break down the factors contributing to a variation around the trend in black oil demand in, for example, the steel industry. In the brief example given, on average, each time there has been a variation in the production of steel this has been half that of total industrial production: the demand for all energy fuels in steel making has varied in sympathy with the production of steel and the demand for black oils has varied twice as much as for all energy fuels in steel making. Thus, for the period concerned, the demand for black oils has varied in sympathy with industrial production.

S. A. Day: Every time production varied once, black oils in steel varied once?

D. A. Lindsell: As a result of weighting each influence.

S. A. Day: It is the variation around the trend rather than the rate of growth over a period?

D. A. Lindsell: The whole point about what we are saying is that we are not really forecasting the rate of growth over time of an individual item. We are stating that there appears to be a propensity for sympathetic variation between industrial production energy consumption and black oil consumption which, if studied, will help us to understand the variations in black oil demand.

S. A. Day: The point I wanted to make is that this project is tied to a particular period of time, when the use of black oils in steel production was increasing rapidly. I would appreciate some elucidation on how you use this weapon for the particular purpose of forward estimating from now.

D. A. Lindsell: We are not using this in forward estimating, if by that is meant the trend of growth. We would not use this method to forecast how much oil will be used in steel making in 1960. We are employing it to try to understand how black oil demand varies and, given assumptions on variation in industrial production in the future, how we might expect that variation to behave. The example given covers only six years, and statistically it is open to a large margin of error.

To make the position quite clear, what we said is that if things happen as between 1948 and 1955, *i.e.* if we have the same sort of economic climate, then we would expect the same variation on average in black oil demand in the steel industry as in the indicator of economic activity we have used, *i.e.* industrial production. Is it true to expect in the future the same sort of fluctuation as there was between 1948 and 1955? There have been two interesting sidelights on this already. One is the question of growing indigenous energy sources, with the allied question of substitution, and the other is the relative cost of these sources. When one has made up one's mind on that sort of thing, one can then look at the table given and, by making appropriate adjustments to the elasticities, see whether the black oil demand might or might not be more or less affected by changes in the economic climate. The important point is that in looking at the future, one has to have the relationships in the past set out beforehand.

G. Chandler: We feel we should not regard this table as sacrosanct; it would undoubtedly need re-calculation from time to time.

C. I. Kelly: Would the authors say what importance is to be attached to this knowledge they are seeking? What does it mean in effect to the refiner or the salesman, to know whether the industry is going to share or not share a fluctuation round the trend?

D. A. Lindsell: I think it is extremely important to have at the back of one's mind some idea as to whether we are going to be confronted with a very large segment of demand which is going to vary more violently or less violently in future with changes in the general economic climate. Obviously this also has an effect on the supply side of the industry.

G. Chandler: Mr Day emphasized that forecasting is more imagination than reason. I would like to say that it is very much more reason than imagination!

Dr E. B. Evans: We are very much indebted to Mr Chandler and Mr Lindsell for dealing with this extremely interesting and difficult subject. Difficult as forecasting or estimating quantities of this kind can be, there are still unfortunate people in the industry who have to make some sort of estimates or guesses as to what is going to happen in order to base future operations, and anything that can be done to aid them by working out methods of approaching this problem contributes a very valuable contribution to the industry, and to economic procedure in general.

The meeting closed with a warm vote of thanks to the authors.

THE LOS BAJOS FAULT AND ITS RELATION TO TRINIDAD'S OILFIELD STRUCTURES *

By C. C. WILSON † (Associate Member)

SUMMARY

The Los Bajos fault may be summarized as a right-hand strike-slip displacement in two stages of over eight miles which cuts across the Tertiary geosyncline along a tear at 112° azimuth, with an oblique uplift of 1700 ft of the N. side in relation to the S. side, and continues obliquely across the SW. corner of the island with undiminished displacement throughout. The movement took place after the deposition of the main body of Pliocene sediments. The tectonic stresses responsible for its formation are believed to have started before the main Andean orogeny but must have reached their greatest intensity after the folding movement, and are believed to have reacted in a direction nearly parallel to the fault plane. It is suggested that the movement was not related to the thrusting movements known to exist in Trinidad. It is possible that in the area of bending of the basement rocks (which is the buried extension northwards of the Guayana Shield) between the shallow area under the Orinoco delta and the area of great subsidence beneath the geosyncline farther to the N., lines of weakness have developed subsequent to the formation of that geosyncline and have had some controlling influence on the direction of the Los Bajos fault.

INTRODUCTION

The Los Bajos fault is a major strike-slip feature intersecting the oilfields from Point Ligoure on the W. coast through Los Bajos, Coora, and Morne Diablo to Negra Point on the S. coast. The fault has caused an eastward displacement amounting to seven miles of the N. face in relation to the S. face. It is therefore of considerable interest in its effect on oilfield structures and the accumulation therein of oil and gas.

In a previous publication by the author (1940), the features of the Los Bajos fault were discussed. Since then additional information has been obtained not only in support of the strike-slip displacement, but also providing a better definition of the true nature of the fault. Opportunity is taken of correcting certain errors which have appeared in subsequent publications in reference to the extent of the fault's displacement.

When the idea of strike-slip faulting was first advanced as the explanation of the fault's displacement, practically no drilling had been carried out near to the Los Bajos fault. Since then the fault has been penetrated by and identified in many wells. Structural conditions also are now clearly established by the development of oilfields in contact with both sides of the fault. In other words, the fault has now been mapped in three dimensions and the amount of its displacement is known.

HISTORY OF INVESTIGATION

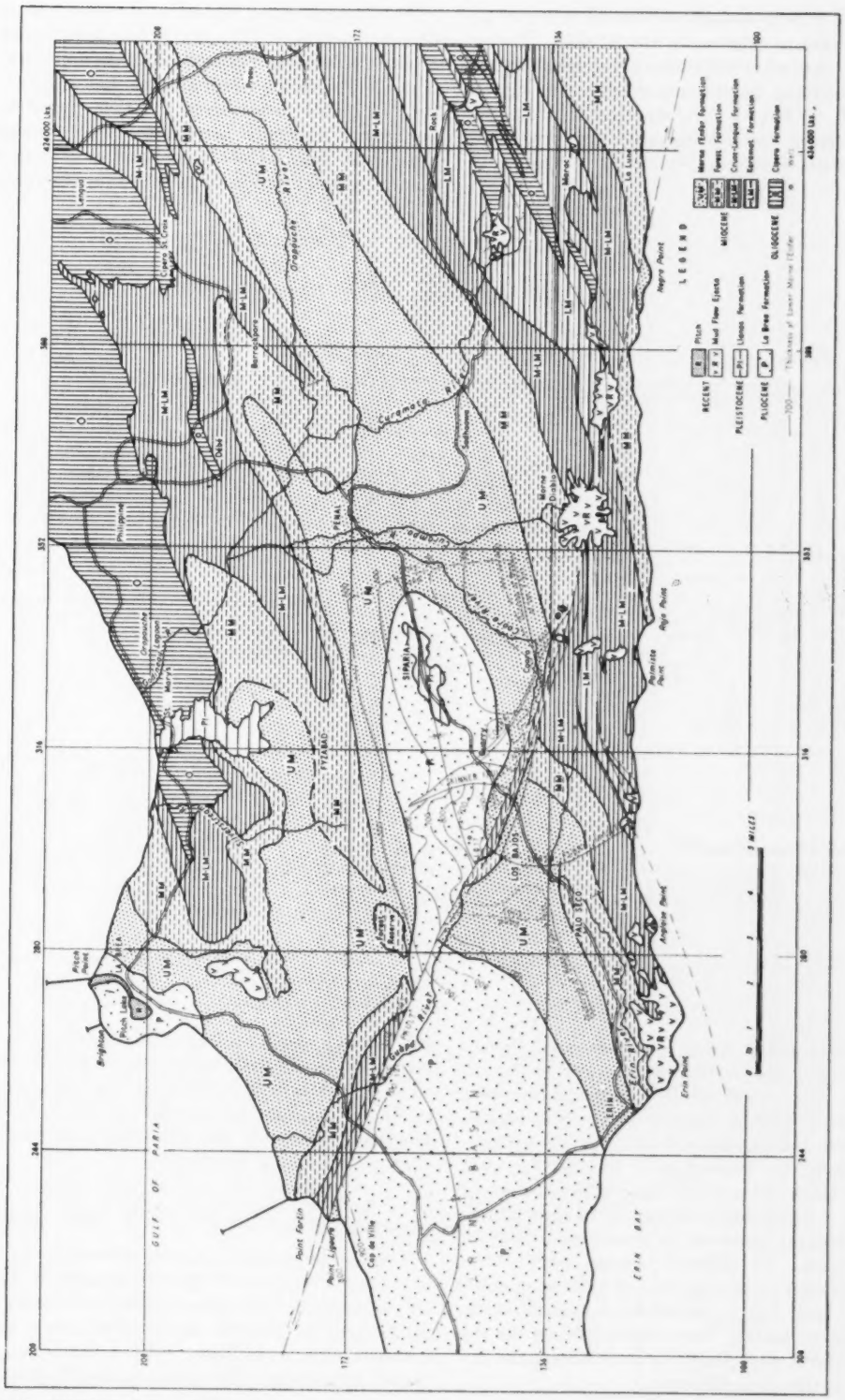
At the beginning of 1929 the author was instructed to carry out a geological survey in South Trinidad, to start at Los Bajos and to proceed eastwards along the N. flank of the main Southern Range anticline, which at that time had only been examined by reconnaissance surveys. He had access to G. A. Waring's publication (1926) and to geological maps, including work by W. J. Reynolds (private communication, 1920) which probably represents the first recognition of the fault's existence. In addition, he greatly benefited by information obtained from geological surveys of SW. Trinidad by H. G. Kugler and G. Ffoulkes Jones (private communications, 1925).

The consensus of geological opinion in the period between 1920 and 1929 asserted that two anticlinal structures existed along a WNW.–ESE. trend which is oblique to the main folding system. The western representative of these two anticlines is the Point Fortin structure, which was believed to be overthrusted to the S. along what was then termed the Guapo fault. Farther to the ESE. lies the Los Bajos structure on the same trend, but this structure was believed to be overthrusted to the N. along a major fault forming its N. flank. The two structures were believed to be separated by an undisturbed saddle exposing Pliocene sediments in the Grande Ravine area, and some geologists considered the possibility of the existence of a hinge fault to explain the changes in direction of apparent throw.

At that time only shallow drilling had taken place in the neighbourhood of the Los Bajos fault. This included 93 wells at Point Fortin and Point Ligoure on the N. side, 20 wells at Los Bajos on the S. side, one well at Mackenzie which was drilled in 1926 and 1927 by the Trinidad Petroleum Development Company and was at that time the island's deepest well, and two wells in the crestal region of the Southern Range anticline 3½ miles S. of the village of Siparia. During 1929 a considerable area between Los Bajos and Rock Dome was mapped and the conclusion was reached during that survey that the displacement of the fault could best be described as a horizontal shift

* MS received 25 October 1957.

† Trinidad Petroleum Development Co. Ltd.


LEGEND
RECENT
Pitch
Mud Flow Ejecta
PLEISTOCENE
Lisnoe Formation
PLIOCENE
La Brea Formation
MIOCENE
Morne l'Enfer Formation
Forest Formation
Cruse-Lengua Formation
Karamat Formation
OLIGOCENE
Cipero Formation
Thickness of Lower Morne l'Enfer
GULF OF PARIA
ERIN BAY
LOS BAJOS
PENAL
SIPARIA
Pitch Lake
Brighton
Point Fortin
Point Ligoure
Cap de Ville
Erin Point
Antilope Point
Negro Point
Icacos Point
Palmiste Point
Agua Point
Guapuche River
Cocoyea River
Cipero
Morne Diablo
Morne
Cruse
Karamat
Forest
Lisnoe
Mud Flow
Pitch
Cipero St Croix
Philippine
Cocoyea Village
Penal
Siparia
Fyzabad
Los Bajos
Erin
Antilope
Negro
Icacos
Palmiste
Agua
Guapuche
Cocoyea
Morne Diablo

of the N. face over a distance of several miles in an easterly direction in relation to the S. side. It was not, however, until after Schlumberger electric logging had been introduced on recommendations by G. W. Halse and H. G. Kugler, in July 1932, that it was possible to form a visual comparison between lithological conditions in various regions on both sides of the fault.

With the continued expansion of the oilfields during a further period of 17 years, it has been found that the fault intersects a petroliferous province and that extensive migration of oil and gas has resulted from this horizontal displacement. These oil accumulations have naturally attracted much development along both sides of the fault, and a corresponding amount of information of great value has been, and

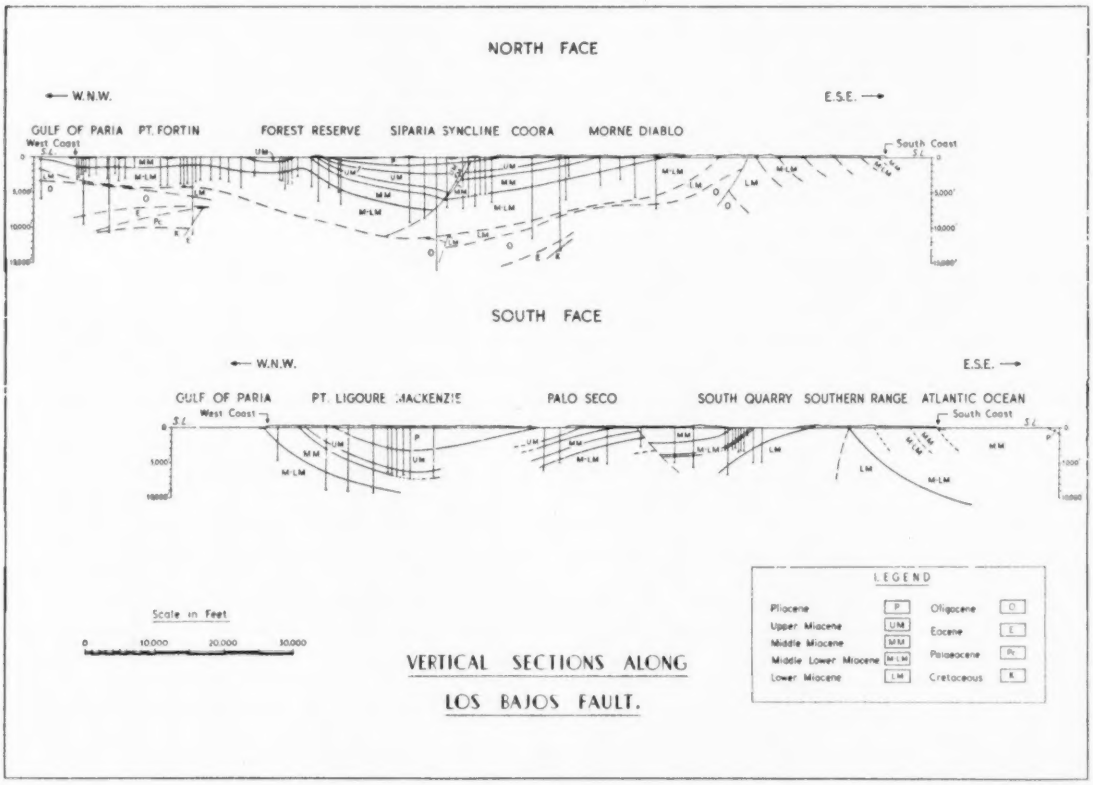


Fig 2

The now established principle of horizontal shift or right-hand strike-slip displacement applied to the Los Bajos fault was conceived by geological mapping alone. Drilling with all the new methods of logging has confirmed and emphasized this interpretation.

Subsequently, as expansion of the oilfields took place, both sides of the fault came under inspection by the drill. Remarkable differences in sedimentary conditions became apparent in juxtaposition on the two fault faces. In addition, strong resemblances appeared between certain sections of wells on opposite sides of the fault but separated by considerable distances along the fault. These similarities on the two sides of the fault were found to bear a constant displacement in the same direction.

still is being, assembled in respect of the fault movement. It is seen from the evidence that the displacement of the Los Bajos fault is now proved conclusively to be a right-hand strike-slip nearly horizontal movement of the N. side amounting to seven miles ESE. in relation to the S. side.

TRACE OF THE FAULT AT THE SURFACE

The Los Bajos fault is clearly defined on the surface at Point Fortin, its westerly manifestation in Trinidad, by the contact of estuarine and shallow water La Brea sandy beds of Pliocene age on the S. face with the comparatively deep water marine Forest and Cruse clayey formations of Middle to Lower Miocene age on

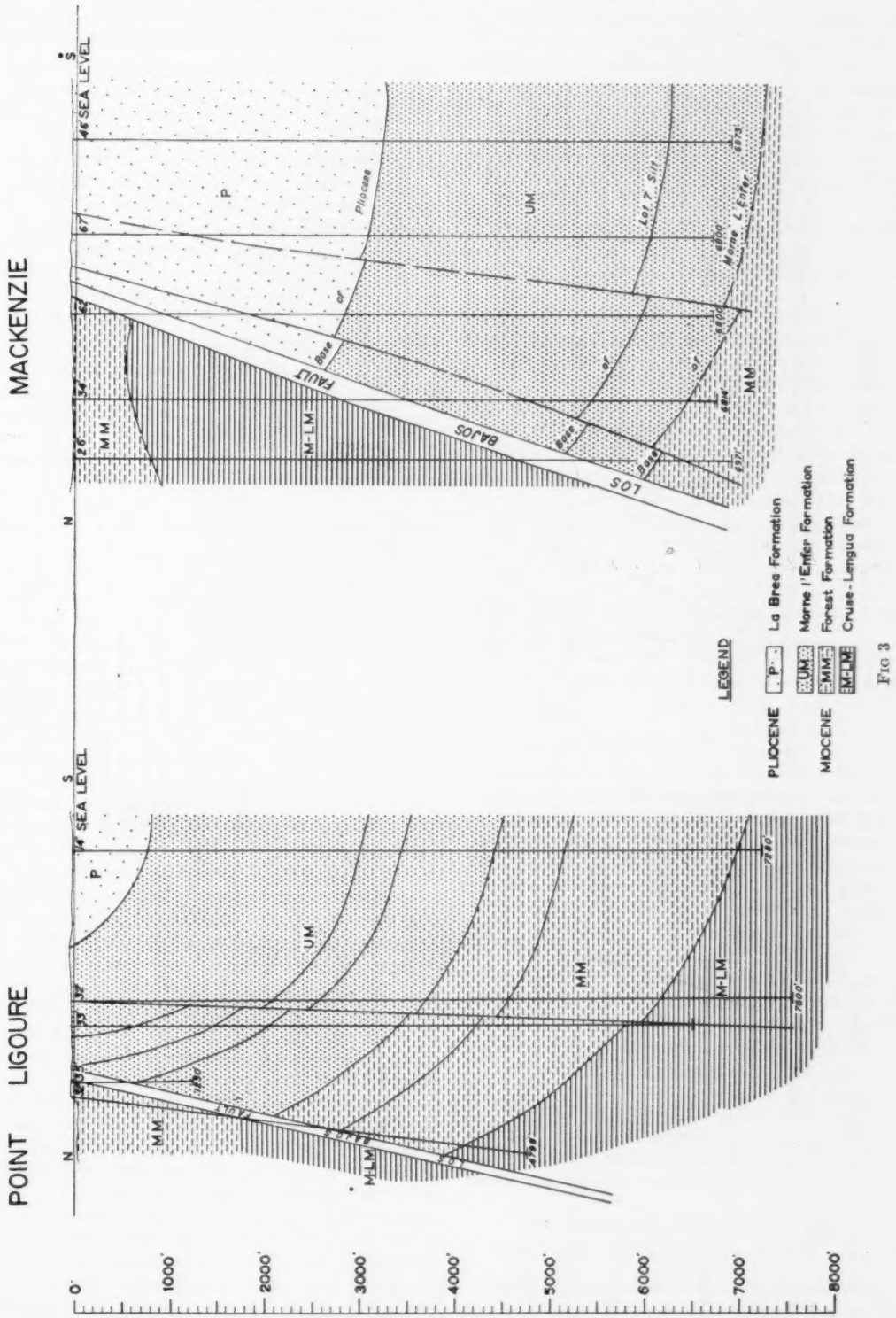

POINT LIGOURE
MACKENZIE
N
S
SEA LEVEL
P
UM
MM
M-LM
Pliocene
Base of
FAULT
BAJOS
LOS
Morne L'Enfer
Lot 7 Sil
LEGEND
PLIOCENE
MIOCENE
La Brea Formation
Morne l'Enfer Formation
Forest Formation
Cruse-Lengua Formation
0
1000
2000
3000
4000
5000
6000
7000
8000

FIG 3

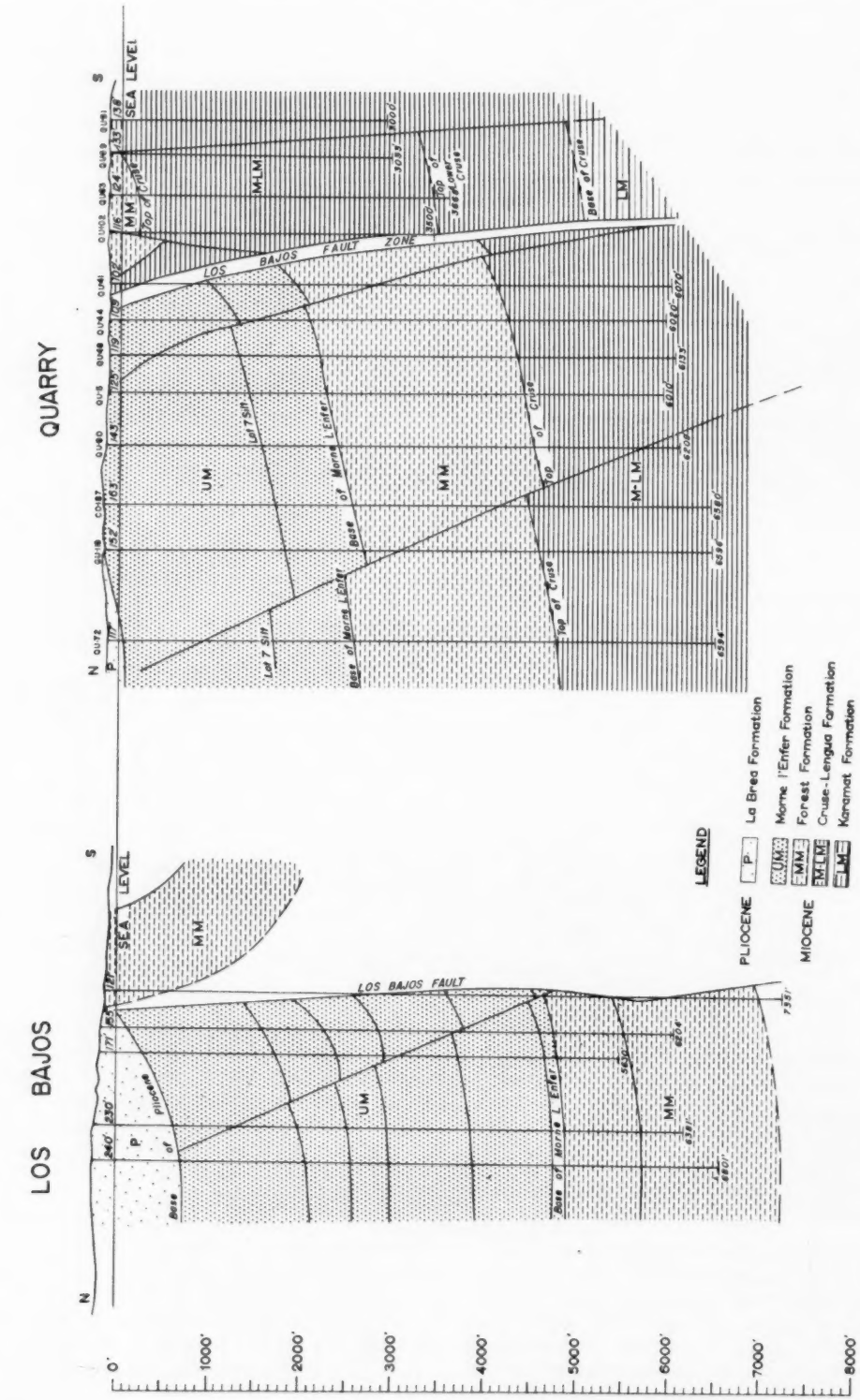

QUARRY
LOS BAJOS
SEA LEVEL
LOS BAJOS FAULT ZONE
LOS BAJOS FAULT
Base of Morne L'Enfer
Top of Cruse
Base of Cruse
UM
MM
M-LM
LM
LEGEND
PLIOCENE
MIOCENE
La Brea Formation
Morne l'Enfer Formation
Forest Formation
Cruse-Lengua Formation
Karamat Formation
0'
1000'
2000'
3000'
4000'
5000'
6000'
7000'
8000'

FIG 4

the N. face. The contrast of sediments on the two sides of the fault is emphasized by four features:

(1) Lateral continuity of sands in the La Brea beds as opposed to the extreme lenticularity of sands in the Forest and Cruse beds.

(2) A strong contrast between predominance of sands in the La Brea beds and predominance of clays in the Forest and Cruse beds.

(3) The La Brea beds show extremely small tectonic disturbance whereas the Forest and Cruse beds here show intense crumpling and slickensiding.

(4) A line of many oil seepages occurs along the fault outcrop.

The fault follows an average course of 112° azimuth across the SW. corner of the island and can be identified over a length of 21 miles on land. It is believed also to continue for considerable distances out to sea off both shores of the island. The course of the fault is not absolutely straight but is slightly convex towards the S., suggesting a rotational movement of the beds on the N. side.

Proceeding ESE., the fault separates the large Erin basin to the S. from the crestal zone of the Point Fortin anticline on the N., and in so doing shows a strongly varying apparent downthrow to the S., increasing from about 5000 ft at Point Ligoure to 10,000 ft at Mackenzie and decreasing to zero in the Grande Ravine area. Still further to the ESE. the throw is reversed. The Siparia basin then appears on the N. face, in front of the Los Bajos anticline on the S. face, after which the fault climbs the N. flank of the Southern Range anticline. Against the deepest part of the Siparia basin the fault places Upper Cruse shales and sands in contact with Pliocene sands, clays, and porcellanites with an apparent downthrow of 7000 ft, this time to the N. E. of the axis of the basin the throw remains continuously at about 7000 ft to the N. until the fault intersects the crestal zone of the Southern Range anticline. In this area disturbance of sediments by the fault becomes mingled with disturbances due to tectonic uplift which is prevalent throughout the Southern Range anticline, particularly where the less competent beds of Lower Miocene age appear at the surface. The trace of the fault therefore becomes confused in the crestal area and hard to determine. It is suspected that a similar difficulty in identification of the trace of the fault may be experienced in the marine areas W. of Point Fortin. There the southern, seemingly unmoved, counterpart of the Fyzabad structure is steeply dipping and faulted against the crestal zone of the Point Fortin structure and may present a corresponding lack of fault definition. In the crestal region of the Southern Range anticline, formations exposed consist of Lower Cruse and Karamat incompetent clays with zones of "Wildflysch" deposits carrying derived fragments of older, pre-Miocene formations. In addition, large areas are covered by recent mud-flow material derived from frequent ejections of mud from still active mud volcanoes occurring along the axis of the anticline. In this crestal region it appears that the fault's displacement is spread laterally over a wide zone of minor faults measuring about two miles in width in which fault drag gives an overall impression of bending of the axis instead of major fracture. The total displacement may be measured by the movement of the anticlinal axis where unaffected by drag or the displacement between the nearest points at which it maintains its normal trend line.

Between the crestal region and the island's S. coast, the dip of beds on both faces is steeply inclined towards the S. The point at which the fault passes out to sea towards the ESE. is not clearly discernible and may be represented by a wide fault system instead of by a single planed fracture. It may be limited eastwards by a point about 2000 ft east of Point Negra, where it separates lignitic shallow water sediments on the S. face from deeper water deposits on the N. face. Other fractures are apparent westwards along the shore for a distance of about two miles from Point Negra. Much sedimentary slumping and suggested deep water deposits render this particular area difficult to explain without considerably more work in the field.

The region in which most detail relating to the fault has been obtained extends between the wells in the North Los Bajos field in the W. and wells in the S. part of the Morne Diablo field in the E. In this area the main fault plane is more clearly defined than in any other sector of its course across the island. Much of this area has been mapped and a contact has been found between extremely well-bedded laterally continuous sandy sediments of Upper Miocene and Pliocene age, and highly lenticular Middle and Lower Miocene sediments comprising Forest, Cruse, and Karamat age. A number of outcrops of rocks containing a heterogeneous accumulation of Lower Tertiary and Cretaceous fragments, sometimes of considerable dimensions, have been identified in close contact with the fault throughout this region. These were previously considered to have been formed by mud-flow ejections contemporaneous with the more normal sediments in which they are interbedded. Now, these beds are interpreted by Kugler (1953) as flysch originating from turbidity currents. Upper Miocene and Pliocene beds, being estuarine and shallow water deposits, nowhere carry "flysch" sedimentation and can easily be distinguished.

OIL IMPREGNATION OF BEDS IN CONTACT AT THE LOS BAJOS FAULT

Petroleum reservoirs in the oilfields associated with the Los Bajos fault (which are Point Fortin, Forest

Reserve (Fyzabad), Grande Ravine, Los Bajos, Quarry, Coora, and Morne Diablo) are predominantly Cruse (Lower Miocene) in age. Forest sands (Middle Miocene) carry a more restricted impregnation. Forest oil reservoirs are confined more especially to the structurally high areas and to the vicinity of major fault zones. Younger sands include the generally very arenaceous sheet-sand deposits of the Morne l'Enfer (Upper Miocene) formation and still more arenaceous sediments of La Brea (Pliocene) age. As a rule, these beds carry fresh water in large quantity. Two main exceptions to this rule may be cited. First, nearly all porous sediments within two miles of the Pitch Lake are saturated with heavy oil. Secondly, a general impregnation of Upper Miocene and Pliocene sands has taken place where these beds are in direct contact with the Los Bajos fault. Laterally this impregnation extends to a distance of only 1500 ft from the fault.

As discussed in a paper by Barr, Waite, and Wilson (1955), oil is considered by many to be indigenous to Cruse sediments and possibly to Forest sediments. It is clear therefore that the younger sandy beds of Upper Miocene and Pliocene age, in which oil was not indigenous, were most likely to have become saturated with oil while in the process of moving over a distance of seven miles past a series of older oil-bearing beds. It is interesting nevertheless to find that Cruse sands generally are lenticular in habit and therefore of restricted volume. However, the sequence of Upper Miocene and Pliocene beds within close proximity to the fault carries a large number of sheet sands which are well impregnated with oil. At the same time, the associated lenticular Cruse sands are still frequently filled with oil. One is led to suppose that older and deeper reservoirs must also have contributed oil and gas along the Los Bajos fault to younger reservoirs, some of which are not generally oil-bearing. Much oil must also have been lost at the surface along the fault during its movement.

MEASUREMENT OF HORIZONTAL DISPLACEMENT

A glance at the geological map gives one the impressions, first, that two main basins exist *en echelon*, each elongated in the ENE. direction of the late Andean trend, and secondly, that the fault occurs along a line of disturbance separating those two basins. The continuity of the line of fracture, regardless of its amount and direction of throw, gave the first indication that the displacement was not a normal vertical throw. It then occurred to the author that possibly the two basins might once have been the same basin which was originally bounded by the same Southern Range structure without interruption. This paper attempts to assemble all the evidence so far obtained, and it is considered that horizontal movement is now proved conclusively. The structure is somewhat complicated by the westward plunging Los Bajos anticline, which appears against the S. face where the fault is in contact with the Siparia syncline. The Point Fortin anticline is also a structure which occurs parallel to the fault. Previously it was suggested (1940) that the fault displacement may have been caused by a component, normal to the fault, of tectonic stresses acting from the NNW. which still existed in the final phase of the Andean episode of folding. However, as explained later in this paper, it now appears that movement along the fault was due to a tectonic adjustment which took place even later than the main Andean orogeny. It also appears that these two anticlines existed before the fault was initiated. If, as we now find, the fault has not been developed by compressive stresses and instead shows characteristic tension faults, then the Point Fortin and Los Bajos anticlines were not formed by the fault. They must have existed previously and formed a line of weakness which may have influenced in some measure the position in which the fault zone was developed. Presumably they presented a line of weakness oriented in a critical direction with relation to the latest development of stress. Measurement of the displacement of the main structural elements, ignoring minor compressional and drag features adjacent to the fault, demonstrates a very considerable movement. For example, the axis of the Siparia basin extended to the fault lies at more than 31,000 ft ESE. of the point at which the axis of the Erin basin intersects the fault.

Four lines of investigation have been pursued with a view to measuring the amount of horizontal displacement:

(1) A correlation of lithological facies changes on the two sides of the fault.

(2) Correlation across the fault of variation in thickness of measurable stratigraphical units.

(3) Similarity of electric logs of individual wells on opposite sides of the fault.

(4) Lateral shift of main structural axes where unaffected by drag.

(1) *Change of Facies during Morne l'Enfer Sedimentation*

Throughout a very large part of the areas of the two basins, La Brea (Pliocene) beds and Morne l'Enfer (Upper Miocene) beds attain thicknesses up to a maximum combined thickness of 7800 ft. They consist of a deltaic and shallow water marine series of many laterally continuous sands interbedded with thin slits and lignites. Correlation of zones in this sequence is infinitely easier than correlation of reservoirs and marker zones in the underlying Forest and Cruse formations, and can be made easily by comparison of electric logs of wells separated even by considerable distances. Cut-out or duplication by

faulting, as well as variations in dip, can be easily detected in some areas by these logs. It is also easy to observe facies changes by this means and the position of such changes on opposite sides of the fault at once shows the amount of displacement by the fault and proves that the main movement of the fault is younger than the deposition of these particular beds. An extremely sharp facies change eastward from sandy to silty sediments occurs S. of the fault along a N.–S. line in Palo Seco and N. of the fault by a similar N.–S. line in the area E. of the Morne Diablo field. A maximum displacement of 44,000 ft is estimated by this means and was reported in the previous publication. Recent drilling in N. Palo Seco has since established the line of demarcation still more clearly between the sandy and clayey facies on the S. side of the fault. Detailed work has been carried out by Favre (private communication, 1955) in correlation of wells drilled between the Fyzabad and Penal fields, and he has found an abrupt lateral change eastwards from sand to clay in Morne l'Enfer beds on the N. side of the fault. Correlation is maintained across this facies change by certain thin sands which persist eastwards. This work has clarified a serious disagreement in correlation of beds mapped at the surface by geologists who have approached the change in facies from opposite directions. The change is apparently due to a rapid increase eastwards in depth of water during sedimentation with the development of a facies carrying a deeper water foraminiferal fauna similar to that of the underlying Forest formation. Unfortunately this facies change has been eroded to the S., leaving a gap of about a mile between the fault on its N. side and the Morne l'Enfer outcrop. The change is clearly represented in the Siparia basin farther to the N. over a distance of at least three miles. Without actual contact of this facies change with the fault, it is not possible to make a direct measurement of displacement, but it is clear that a movement of at least 37,000 ft took place.

(2) *Comparison of Thickness Variations between Key Markers in Lower Morne l'Enfer Formation on the Two Sides of the Fault*

An isopachyte map has been prepared to show the interval between the base of the Lot 7 silt and the base of the Coora silt in the Lower Morne l'Enfer formation. These two zones are used because they are most widespread in extent and are clearly identified throughout a considerable area. Strong variations in the thickness of this interval are displayed in well sections; the isopachyte map conveniently shows these variations and their comparison on the two sides of the fault. Similar variations in thickness take place proportionately throughout the Morne l'Enfer sequence, but markers are less well known in the upper sections, and changes in thickness are therefore more difficult to map with certainty.

A remarkably rapid thickening of this interval from NW. to SE. occurs down the S. flank of the Fyzabad anticline near to the N. face of the fault and is terminated at the contact of this interval with the Skinner fault. This is a normal fault which runs northwards from the Los Bajos fault at about two miles E. of the village of Los Bajos. The maximum displacement of the Skinner fault is a 2400-ft downthrow to the W. at its contact with the Los Bajos fault. It completely vanishes northwards in a distance of about two and a half miles. The thickness of Lower Morne l'Enfer beds W. of the fault is 1300 ft, while immediately across the fault to the E. it is only 900 ft. A similar degree of thickening also persists in all younger Morne l'Enfer beds on the W. side of the Skinner fault.

Assuming that the Los Bajos fault caused a horizontal movement of beds on its N. side by seven or eight miles eastward, then it may be inferred that a similar thickening of Lower Morne l'Enfer beds and a similar normal fault must occur S. of the Los Bajos fault at a corresponding distance westwards from the Skinner fault. A seismic reflection survey has been carried out over this particular area, and an abundance of reflected dips were recorded by this survey. Although no fracture zone was identified, the dips recorded continuously throughout the area are much too gentle to provide an unbroken correlation of Morne l'Enfer beds between NW. Palo Seco and Mackenzie. In fact, the discrepancy revealed by these dips amounts to a normal throw comparable with that of the Skinner fault. It is hoped that this additional link in the evidence will be confirmed in the fairly near future by the drilling of wells near to the fault on its S. side.

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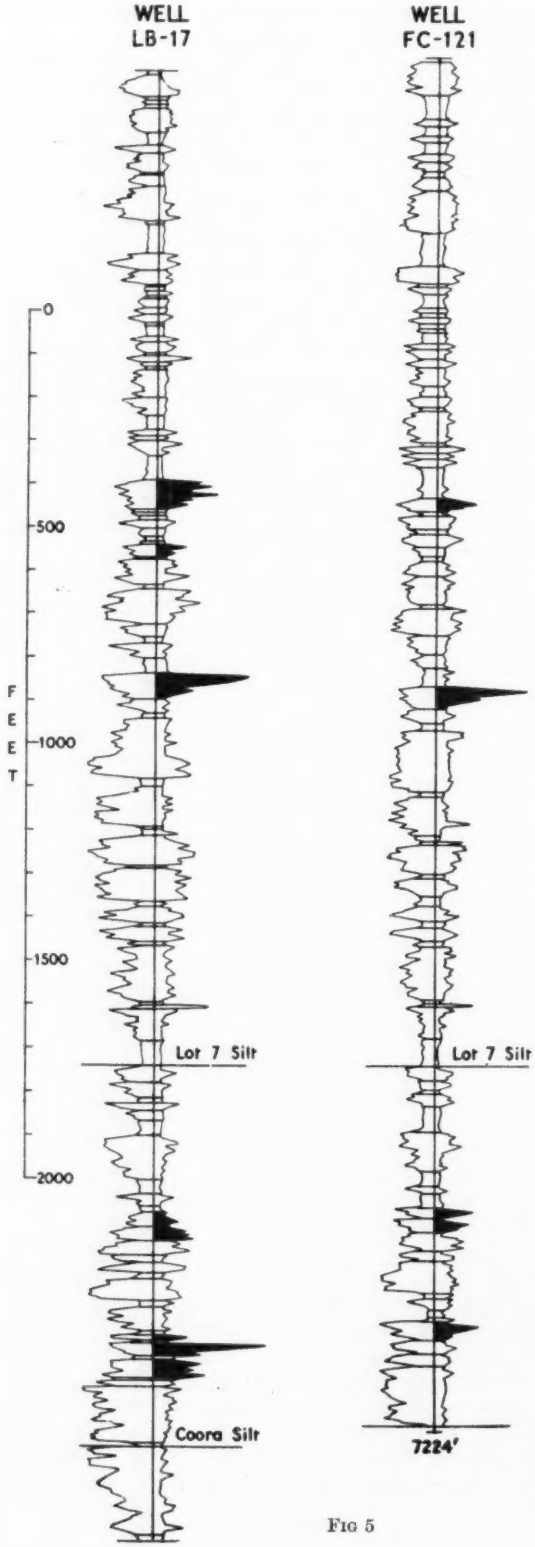

FIG 5

Los Bajos fault. At that time the Skinner fault had not been discovered. It is now clear that the abrupt difference in thickness of Lower Morne l'Enfer beds on the sides of the Skinner fault means that the Skinner fault developed during the deposition of the Lower Morne l'Enfer formation and not after these beds had been laid down. It appears now that the Skinner fault was caused by an increased local subsidence within the Siparia basin and may have been due to differential compaction of clays and sands in incompetent Forest–Cruse beds below, and occurred long before the Los Bajos fault took place.

The abrupt development locally of sands in Lower Morne l'Enfer beds at their southern outcrop against the E. face of the Santa Flora fault, in a region where these beds are generally argillaceous, suggests a similar local subsidence to that suggested in the case of the Skinner fault.

Similarities in thickness of the Lower Morne l'Enfer formation are shown on the N. edges of the two basins. With this similarity it is possible to match the S. flank of the Point Ligoure structure with the S. flank of the Forest Reserve anticline. Similarity is now also being obtained between sand distribution and thickness between NW. Palo Seco, Grande Ravine, and S. Coora fields. The balance of the evidence favours the idea that the two basins once formed a single sedimentary unit.

(3) *Similarity of Electric Well Logs on Opposite Sides of the Fault*

A remarkable resemblance between electric logs of wells seven miles apart and separated by the fault has been found. For example, a well in Point Fortin Central and a well in E. Los Bajos may be cited. In these two wells sand distribution and individual lignite layers are identical. Even the oil and gas distribution shows a selective impregnation of sands which correlates exactly. The present distance between these wells is 37,000 ft. This phenomenon is repeated between a well at Point Ligoure and a well at W. Forest Reserve with a similar amount of displacement. Similarity of logs is also demonstrated between NW. Palo Seco and Coora.

(4) *Lateral Shift of the Main Structural Axes by the Fault where Unaffected by Fault Drag*

(*a*) Displacement of the axis of the Southern Range anticline at outcrop suggests more a warping by drag than by a single major fracture. This displacement may instead have been distributed along many small faults. The resultant effect nevertheless is the same, and a measurement of the displacement of the axis of the Southern Range anticline may be measured by projection towards the fault of the two separated structural lines where they lie parallel to the Main Andean trend. By means it is calculated that

the displacement is 32,000 ft. A similar warping of trend is suggested without actual fracture by the change, and a WNW.–ESE. strike between the Moruga Hills and the Trinity Hills.

(*b*) Displacement measured by the shift of the two components of the Forest Reserve–Fyzabad anticline is complicated by the fact that its southern component lies under the Gulf of Paria to the W. of Point Fortin. The total displacement of this structure is, however, more than 32,000 ft.

(*c*) The most rigid structure which has suffered displacement is the Erin–Siparia syncline. The shift of the axis of this structure amounts to 32,000 ft.

MEASUREMENT OF VERTICAL DISPLACEMENT

The deepest region of the Siparia basin may be compared by markers in the Morne l'Enfer sheet sand series with their equivalents in the deepest region in the Erin basin near to the Los Bajos fault. The Siparia basin is found by this measurement to be 1700 ft shallower than the Erin basin. This indicates clearly that during the horizontal movement of seven miles towards the E., beds on the N. side were also elevated by 1700 ft.

FEATURES OF INTEREST SEEN IN ASSOCIATION WITH THE FAULT

(1) *Direction of Movement of the Los Bajos Fault*

The fault was described as a displacement of beds eastwards on the N. side. It could also be described as a displacement of beds westward on the S. side. This should be judged by which side is the most stable tectonically. The Guayana Shield outcrops along the S. bank of the Orinoco River and extends northwards over a wide area towards Trinidad, sloping gradually under the Orinoco delta and Llanos plains of Venezuela, deepening first gradually, then sharply (near S. Trinidad) under the Tertiary geosyncline. Less stable tectonic conditions occur to the N. of the fault, where sediments approach the Andean folding of the Northern Range. It is therefore considered that the Guayana Shield, which has remained relatively unmoved since the beginning of sedimentation, presents the more stable of the two fault blocks. It is thus assumed that the S. side of the fault has stood firm while the N. side has broken off and moved towards the ESE.

(2) *Disturbances of Beds at Outcrop of Fault Zone*

In the region between the eastern Los Bajos field and the Morne Diablo field, five miles farther to the E., an area of steep dips (mostly vertical and overturned) exists as a strip 2000 to 3000 ft wide extending to roughly equal distances on each side of the fault. In the early days of the development of the Coora and Quarry fields it was feared that all beds underlying this disturbed zone would be crushed and broken to such an extent that, commercially, productive reservoirs could not exist therein. However, drilling extended successfully as far as the edge of the disturbance and was ultimately tested even within the area with equally successful results. It was found that the disturbed zone narrows quickly with depth, and the fault under effective cover becomes reduced nearly to a single plane. Disturbed dips in the areas where competent beds with substantial thickness are in contact with the fault are mainly superficial. Section 4 demonstrates this effect and shows how extremely limited is the steepening of dip.

(3) *Tension Features as Opposed to Compression*

Section 4 also demonstrates clearly that the area here, instead of being under compression, has been in a state of tension and collapse.

A similar phenomenon also occurred on the S. face of the fault between the Point Fortin structure and the Erin basin, although the attitude of apparent throw is completely reversed.

Between these two regions, *i.e.* towards the apparent saddle near Grande Ravine, disturbance of outcropping beds is extremely restricted. This does not mean that the moved formations here are covered and concealed by moving sediments. It appears from well sections that the fault has displaced even the outcropping formations. Lack of disturbance may be explained by the fact that a considerable thickness of competent beds is here in contact on the two sides of the fault.

W. of the saddle incompetent formations reappear at the surface, but this time on the N. face of the fault, whereas the most competent unit of any part of the region occupies the S. face. As previously mentioned, the direction of throw is reversed and tension fault features appear in this competent unit.

It is characteristic therefore that the fault plane always dips towards the apparently upthrown side. The upthrown side thus appears to be overthrusted and therefore to be a compression feature. This, however, is not the case, because the competent face in each case shows normal tension faulting.

Consider for a moment the initial stages of the fault movement. It would be most unlikely that a crack across country would form as a straight line. It is likely that it would be extremely jagged or sinuous. However, during movement over considerable distances the irregularities would be subjected to greatest sheer and faults approximately parallel to the main direction of displacement would develop across these irregularities so that the fault would become a complex sheet zone with local regions of

compression and tension dependent on which side of a major irregularity these regions occurred.

At the time of the author's previous publication in 1940, well evidence in immediate contact with the fault was scarce and these tension features were not appreciated. The thrusted appearance all along the fault was therefore responsible for the view that the Los Bajos fault was formed under compression and was thrusted by a component of tectonic stresses still acting from the NNW. during later Pliocene time.

(4) *Deep-seated Movement as Opposed to Low Angle Thrusting*

The stresses which were responsible for the displacement may therefore have belonged to a movement later than the main Andean orogeny and acted more nearly parallel to the plane of the fault. The fault has cut completely across a competent basin of considerable size, as well as across the flanking anticlines in an area where the geosyncline has attained its greatest development and where the Tertiary sequence has attained a thickness of at least 18,000 ft. It is considered therefore that the fault may be deep-seated, cutting across country as it does without regard for competence of formations and structures exposed at the surface. It was suggested by Bucher, Kugler, and Suter that the fault rises to the SE. and becomes a low-angle thrust whereby stresses are completely released at the surface. The thrust fault therefore which has been identified as forming a strong feature in the S. flank of the Southern Range anticline at Rock Dome has been suspected as having taken up a large part of the Los Bajos fault movement.

The objections to this hypothesis are: (*a*) the throw of the thrust is only about 13,000 ft, whereas the Los Bajos fault resulted in a displacement of at least 35,000 ft; (*b*) there appears to be considerable evidence that the Rock Dome thrust took place early in the Miocene and terminated at the end of Karamat time. The main movement of this thrust is overlapped by Cruse beds exposed on both plunging noses of the anticline. The 35,000-ft displacement of the Los Bajos fault, on the other hand, has been measured in youngest Miocene beds and is believed to have taken place much later still; (*c*) it is believed that a major thrust has displaced pre-Miocene sediments S. of the fault by a corresponding amount to that on the N. Evidence of such thrusting S. of the fault is suggested by the excessive Cruse thickness found to exist in Erin Well No. 3 and may be a characteristic feature of the Southern Range anticline.

H. G. Kugler mentioned that a NNW.–SSW. trend, oblique to the main trend, can be seen in a number of locations in Central and S. Trinidad. This trend is developed as a number of assymetrical folds affecting Miocene beds, carrying their steeper thrusted flanks inclined to the E. This trend is at right angles to the fault movement and possibly suggests a frontal wrinkling of the moving unit where it may be rising on an eastward shallowing basement.

(5) *Horizontal Slickensiding in Fracture Associated with the Fault*

Higgins has shown in Southern Morne Diablo an excellent exposure of a fault carrying the characteristic strike of the Los Bajos movement. Strongly slickensided dark grey shales on the S. face lie in faulted contact with well-bedded grey oil-stained sands occasionally interbedded with light grey and brownish silty clay partings on the N. face. Clear evidence of horizontal slickensiding may be seen, especially within the main plane of faulting. Other small planes of displacement are exposed in this section N. of the main fault plane, and adjustment faulting can also be identified. This main fault does not necessarily carry the entire displacement of the Los Bajos fault; it probably forms an edge of a moved segment of which there must be a very large number throughout the length and breadth of the Los Bajos fault. As mentioned previously, faults probably developed parallel to the movement at the base of irregularities in the original trace of the fault, and when movement became established, a series of lozenge-shaped blocks, elongated in the direction of movement, were developed and these, with the development of slickensided polished surfaces, formed a lubricant between the limits of the fault zone.

Striations on the surfaces of these blocks would lie parallel to the direction of movement and be nearly horizontal. Other evidence of horizontal slickensiding was given by the late A. G. Hutchison with a core sample of Cruse Clay from a well within the fault zone. Nearly horizontal striations were found also near the outcrop of the fault at Point Ligoure.

(6) *Lubrication*

Oil migrating along the fault zone will naturally assist in the lubrication of the moving parts within the fault zone and will also concentrate in areas of tension where open fractures may be preserved. An excellent example of oil impregnation in association with slickensided clays within the fault zone has recently been excavated in the South Coora field. Here blocks of coarse Herrera grit, rounded pebbles of Naparima Hill formation, and fragments of marly clay interspersed with oil-sand blocks are squeezed into a lubricated mass easy to move by the fault.

(7) *Flysch Deposits*

These deposits are generally found here as ungraded gritty clays which carry fragments of Cretaceous and Lower Tertiary formations. They occur at a number of horizons in Lower and Middle Miocene (Cruse and Forest beds) and are most abundant at the base of the

Miocene. Previously they were considered to have been ejected, and sometimes even injected as mud flow by mud volcanoes contemporaneously with the deposition of the associated beds. A number of such formations have been mapped in close contact with the fault. These deposits are some of the least competent formations in the Trinidad sequence and may form plastic material within the fault plane.

COMPARISON OF LOS BAJOS FAULT WITH THE STRIKE-SLIP FAULT SYSTEM OF CALIFORNIA

Similar but far grander and more extensive features are displayed in California by horizontal movements during Miocene to Recent time along the San Andreas, San Gabriel, and other related faults. These faults have moved sediments to distances totalling five or six times the amount measured along the Los Bajos fault. At the same time there is no indication of change over into low angle thrusts. B. W. and R. Willis (1928) state that in California shearing has been repeatedly renewed ever since Cretaceous time. They state that a force directed from the SSW. impinging on the continent at an angle of 45° would produce a rotational stress in a horizontal plane. J. C. Crowell (1952), dealing with the San Gabriel fault, describes extensive lateral displacement under conditions similar to those associated with the Los Bajos fault. He describes a displacement of outcropping basement rocks amounting to more than 15 miles.

EVIDENCE OF RELATIVE HORIZONTAL MOVEMENT IN AREAS NOT CONNECTED WITH THE LOS BAJOS FAULT

(1) Abundant low-angle slickensiding at a wide variety of localities has been observed in cores, especially those taken in the more competent beds of Cretaceous age. It would seem therefore that horizontal movement is not confined to the displacement by the Los Bajos fault, but rather that the region of at least the S. half of the island has suffered a general torsion.

(2) A considerable number of examples of slickensiding along the bedding-planes has also been observed.

(3) A fairly large-scale warping of structures is visible and appears to be especially associated with the Southern Range anticline. In this warping it appears that a horizontal displacement has taken place without seriously breaking the main structures. Two examples of this phenomenon may be cited: (*a*) the change of direction from E.–W. to ESE.–WNW. and back to ENE.–WSW. between Cedros and Palo Seco both on the axis of the Erin basin as well as on the line of mud volcanoes which is believed to mark roughly the crestal zone of the Southern Range anticline; (*b*) the change of strike direction from ENE.–WSW. in the Moruga structure, to ESE.–WNW. along the Canari River, and returning to ENE.–WSW. in the Goudron Guayaguayare structure.

It is still uncertain whether or not these changes in strike are due to variations in horizontal movement, or whether they are entirely due to buried variations in structure or lithology. However, they have acquired their existing form later than the main Andean folding and must be due to tectonic stresses prevailing during the development of the Los Bajos fault.

AGE OF THE LOS BAJOS MOVEMENT

A. G. Hutchison and P. Leicester, in their examination of the region surrounding the Los Bajos anticline and its contact with the Los Bajos fault, considered that movement started early in the Miocene and proceeded in stages until late Pliocene. The observations here mainly concern beds which show lateral continuity and in which measurements of displacement can be made with accuracy. These beds are Morne l'Enfer in age (and younger) and belong to the Upper Miocene and Pliocene respectively. These beds alone have been moved a distance of at least 37,000 ft. If the fault started early in the Miocene time, *i.e.* before Morne l'Enfer beds were deposited, then the total displacement is greater than 37,000 ft.

The time at which measurable displacement took place must naturally be later than the age of the beds which were displaced. Most of the evidence of horizontal movement put forward is shown by the sheet sand series of Morne l'Enfer and La Brea formations. In the Mackenzie area of the Erin basin more than 3000 ft of La Brea (Pliocene) beds lie in fault contact with Cruse beds and it is believed that this thickness represents almost the entire sequence of Pliocene beds belonging to S. Trinidad. Siparia beds of Pleistocene age cover a considerable area in the Siparia basin. S. of the fault Siparia beds have not been identified, but further investigation may prove whether or not these beds have also been displaced horizontally. The author has been asked whether any movement has been discovered within living memory. At least 120 wells have now passed through the fault, and these should be particularly sensitive to earth movement. In none of these has there been any report of casing failure due to natural causes. No earth tremors have been recorded in direct association with the Los Bajos fault. It may be said therefore that present-day movement along the fault is non-existent.

J. C. Crowell, referring to the San Gabriel fault of S. California, gave evidence of a consistent deflection of stream channels. The San Gabriel fault is moving actually at the present day, and streams which cross

the fault are continually having their downstream sections moved by the fault away from their upstream sections and a similar Z bend is then formed at the fault at each stream crossing. E. Rod (1956, p. 466) also describes very distinct stream displacements of this type due to strike-slip faulting in N. Venezuela.

Topographical maps of outcrop of the Los Bajos fault, especially where competent beds are in contact with at least one face of the fault, have therefore been examined. No evidence of movement which affects the present drainage pattern can be found. In the Coora–Quarry field a clear fault feature is shown as a line of depression. A number of streams cross this feature at right-angles but show no zig-zag pattern whatsoever. It is considered, therefore, that the period of movement amounting to seven miles displacement occurred after Pliocene and before recent time.

The author has attempted to account for a considerable difference in the amount of displacement found in his four separate measurements. These measurements may be compared as follows:

(1) The lithological facies change has been moved by 44,000 ft, unless it is assumed that the outline of the facies change takes a sharp bend to the W. in the area which is now eroded.

(2) Variations in thickness between markers cannot be measured with any degree of accuracy until the region between Grande Ravine and Mackenzie is drilled up.

(3) Similarity of electric logs of individual wells gives a movement of 37,000 ft, but again cannot be measured with any great accuracy without further drilling.

(4) A remarkable consistency of measurement has, however, been found between the displacements of the three main structural features. These have all moved a distance of 32,000 ft.

It is suggested that the 12,000-ft difference between displacement of lithology and displacement of structure may prove to be valuable evidence that at least two stages of movement can now be identified and measured. The following chronological order of relevant events is suggested:

(*a*) Deposition of Morne l'Enfer and La Brea formations.

(*b*) A strike-slip movement eastwards of 12,000 ft along the same fracture as that of the Los Bajos fault.

(*c*) The main development of structure locally along the Andean trend and the development oblique to that trend of the Point Fortin and Los Bajos anticlines.

(*d*) The main and final strike-slip movement eastwards of 32,000 ft.

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THE DISTILLATION OF BINARY AND TERNARY MIXTURES*

By A. K. QURESHI† and W. SMITH‡

SUMMARY

At a constant flow rate and total reflux the separation of binary and ternary mixtures by a wetted-wall column has been measured. It has been found that the height of a transfer unit, calculated from these measurements, depends on the concentration of the mixture in the column, as has been found by many other workers. For binary mixtures a simple function which is substantially independent of the concentration of the mixture has been devised empirically for the performance or efficiency of the column.

It is pointed out that in multi-component mixtures it is possible to ascribe a different value of the efficiency of separation to each component, and that the height of a transfer unit for each component of a ternary mixture is different is shown by the experimental results. It is concluded that for practical purposes it is possible to use the performance measured during the separation of binary mixtures for calculation of the separation of ternary mixtures. A discussion of the transfer unit theory as it applies to ternary mixtures is appended.

Equilibrium data and the refractive index and density at 20° C for the two ternary mixtures—heptane–methyl *cyclo*hexane–toluene and acetone–chloroform–benzene are included.

NOMENCLATURE

a	Area of interface per unit volume of packing.
G	Molal flow rate of the vapour phase.
h	Distance up the column from the bottom.
H	Total height of the column.
H_e	$H_{OG}y(1-y)$
H_{OG}	Height of an overall transfer unit in vapour phase, and calculated using Whitman's theory.
K_e	$K_G/y(1-y)$
K_G	Overall mass transfer coefficient.
S	Cross-sectional area of the column.
x	Mol fraction in the liquid phase.
y	Mol fraction in the vapour phase.
y^*	Equilibrium value of x.

Subscript T—top of column, B—bottom of column.

INTRODUCTION

THE fact that the performance of packed distillation columns is a function of the concentration of the mixture being separated, or some related variable, has been reported by many workers.[3-5,15,17,19,22] Usually the performance has been represented by the height of a transfer unit—generally H_{OG}, based on overall vapour concentrations and calculated by assuming that the Whitman two-film mechanism is obeyed. With all other conditions the same the H_{OG} for a binary mixture has a minimum value and becomes very large as the mixture becomes pure in either component. Although Whitman's mechanism and other mechanisms of mass transfer which have more recently been devised [2, 7, 8] all predict that the H_{OG} should show a slight dependence on concentration, by reason of the relationship between the film coefficients of mass transfer and the physical properties of the mixture, the variation in value measured experimentally is many times greater than that specified by any theory. Nor does any theory predict a minimum value in H_{OG}. This fact has initiated much fundamental work in recent years, but no satisfactory theoretical answer to the problem has yet been found.

The performance of a packing is often given as a function of the throughput of material: it is rare that its dependence on concentration is noted. One can generally assume in this case that the value of H_{OG} quoted is at or near its minimum, the average concentration in the column during measurement having been such as to ensure this. It is then difficult to estimate the performance when the mean concentration has some other value. The first part of this paper describes an empirical method of allowing for the effect of concentration.

It was discovered that it is not possible to deal with a ternary mixture in the same way. In a binary mixture the H_{OG} calculated from the measured separation in a distillation column is bound to be the same whether the separation of the more volatile component (m.v.c.) or the less volatile component (l.v.c.) is used in the equation defining H_{OG}. This is ensured by the algebraic form of the relationship between the concentration of the two components (see Appendix 1 (*a*)). However, once a third concentration variable is introduced, the equality of H_{OG} for each component is not assured even though, as for a binary mixture, Whitman's theory requires that they should be the same (see Appendix 1 (*b*)). This problem has been examined theoretically in several ways.[10,20,21] In practice, this means that values of H_{OG}, calculated from the concentration change of different components in the same column in the same experimental measurement, are likely to be different. Again, as for binary mixtures, this is caused by a breakdown of the theory. In this paper values of H_{OG} for each of three components measured for many different concentrations of a ternary mixture are given, and the way in which these values depend on concentration and their behaviour under various conditions is discussed qualitatively.

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APPARATUS

For the purposes of this work the chief measurements required were point values of H_{OG} for a wide range of values of the concentration of mixtures being separated by a packed distillation column. Point values are most easily obtained by measuring the separation of a mixture over a short length of column, such that the concentration change is small, preferably not greater than the interval corresponding to one theoretical stage. However, to place two sampling points one above the other in a packed column in order to measure a concentration change of this order would be undesirable. Their distance apart would be too small to ensure that the removal of a sample from one point did not affect the concentration of the sample which should be taken simultaneously from the other point. It is in any case difficult to obtain representative samples of either phase from the centre of a packing. An alternative method, namely, to take samples from the condenser and reboiler with only a very short length of packing between is also unsuitable. Apart from the unknown amount of rectification in the reboiler and condenser, an assessment of the extent of end effects in the packing would be difficult and the character of the phase flow in the packing would be uncertain.

For these reasons a wetted-wall column was used in this work. Although in a wetted-wall column the separation of the mixture is small, the length of the separation section is large and end effects can be confined within a short distance of each end. By careful design, rectification in the reflux return and condensing equipment can be kept small and, by taking samples of the liquid just after it leaves the wall at the bottom of the column, the effect of rectification in the reboiler equipment can be excluded from the measurements.

The assumption is made, however, that the nature of the distillation process in a wetted-wall column is the same as that of a packed column. There is no reason why the mass transfer mechanism itself should be different; but in a wetted-wall column the flow of the phases is much less disturbed than in a packed column. Apart from the formation of ripples on the surface of the liquid film, the flow in a wetted-wall column is undisturbed, and by no means resembles the discontinuous pulsating liquid movement observed in a packed column. (Since it was considered that a wetted-wall column operating with ripples rather than without ripples in the liquid film more closely resembles in behaviour a packed column, no attempt was made to suppress rippling.) It was found by comparison with some previous work [17,19] that H_{OG} for a wetted-wall column bears the same kind of relationship to concentration as it does in a packed column (v.i.).

A diagram of the equipment, the principal parts of which were made in glass, is shown in Fig 1. Vapour from the reboiler (S), a 3-litre flask, was introduced into the centre of the bottom of a 134-cm long and

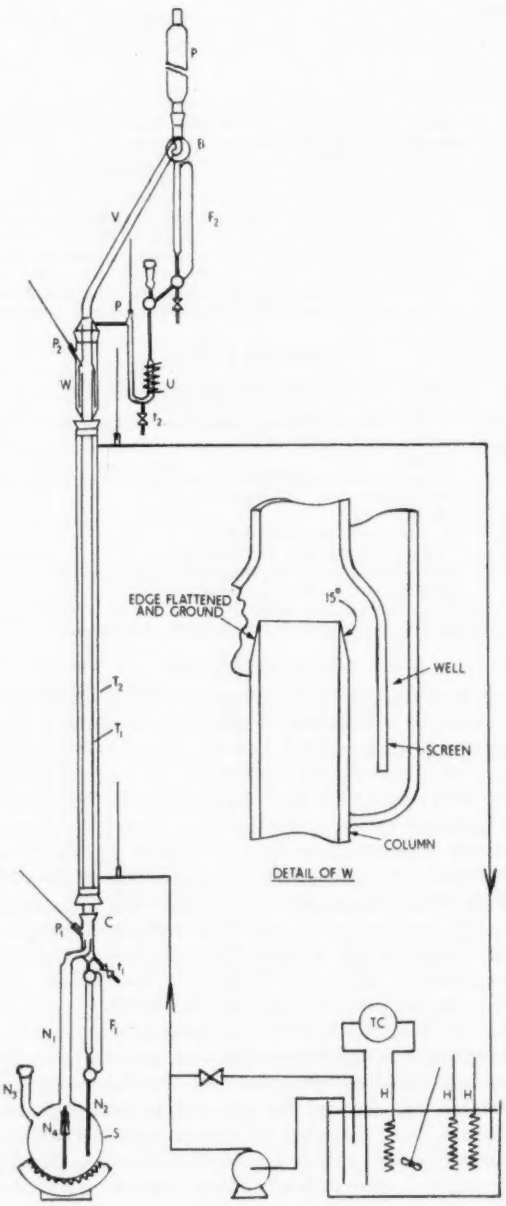

FIG 1

FLOW DIAGRAM OF APPARATUS

2·5-cm i.d. glass column, the wetted-wall section of the equipment. Liquid from the bottom of the column was collected smoothly (C) below the level at which vapour was fed in, passed through a capillary

flowmeter[15] (F_1), and returned to the reboiler. At the top of the column the liquid reflux was measured by another capillary flowmeter (F_2) and then led through a reflux heater (U) back into the main tube. It was found that if the liquid was first calmed by a glass screen and then passed over a lip flattened and bevelled to an angle of 15° (Fig 1 detail) an undisturbed film was straight away obtained, although rippling in the main part of the column was not prevented. The vapour from the top of the wetted-wall column was kept out of contact with the liquid as far as possible. It was led to the condenser through a tube (V) heated to a temperature well above the condensation point of the vapour, thereby preventing further rectification.

The wetted-wall section of the equipment was jacketed throughout its length with a 5-cm i.d. glass tube. Glycerine–water mixtures were pumped into the bottom of this jacket at the temperature of the liquid inside the column at that point. The rate of flow was chosen so that the temperature of the glycerine solution when it reached the top of the jacket was the same as the temperature of the liquid reflux. The rate of fall in temperature (T_2) or the temperature gradient along the tube, caused by loss to the surroundings outside the jacket, is not necessarily the same as the temperature (T_1) gradient of the liquid inside the tube, fixed by the rate of rectification. However, the change in temperature of the liquid inside the tube is small, and the maximum temperature difference across the wall of the inside tube will be very small.

PROCEDURE

All the experimental results used in this paper were measured at atmospheric pressure at total reflux and at the same flow rate. (Between 0·95 and 1·1 g/sec for heptane–methyl*cyclo*hexane–toluene—Reynolds No. in the vapour phase 2750 to 3000; and between 1·05 and 1·25 g/sec for acetone–chloroform–benzene—Reynolds No. in the vapour phase 3450 to 3800.[15]) A mixture was placed in the still, the composition being chosen by experience to give the desired value of the mean concentration in the column. The reboiler and reflux line heaters were adjusted to give the required flow rate, and the temperature and circulation rate of the glycerine chosen to give adiabatic conditions. After a period of about one hour in order to allow conditions to become steady, two sets of samples were taken at intervals of half an hour. A sample of the bottom product was first removed from the liquid line returning to the reboiler (t_1). Since the quantity of liquid in the reboiler is large compared with the quantity of mixture in the rest of the equipment, conditions in the column were only slightly affected. A sample from the top of the column was then removed as quickly as possible from the reflux line (t_2). If analysis showed that the composition of the two samples from the same point was within 0·002 mol fraction (0·0002 in refractive index), the readings were recorded.

The composition of samples of binary mixtures was determined by measuring their refractive index at 20° C with an Abbé refractometer (reading to three decimal places with interpolation of a fourth). For this purpose about 0·5-ml samples were required. In order to measure the composition of ternary mixtures another property of the liquid sample must be measured. It was found to be most convenient to measure the density, and this necessitated a sample of about 6 ml (a 5-ml S.G. bottle being used).

PHYSICAL DATA

Two ternary systems, heptane–methyl*cyclo*hexane–toluene and acetone–chloroform–benzene, were used in this work. The physical properties of these two systems and the two sets of three binary pairs making up each ternary mixture were determined.

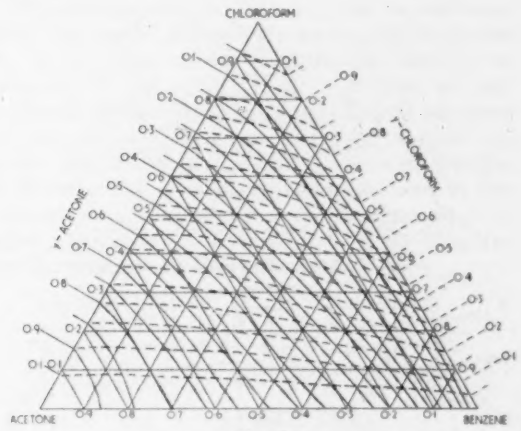

FIG 2

ACETONE–CHLOROFORM–BENZENE EQUILIBRIA

Equilibrium data at atmospheric pressure for the six binary mixtures were obtained from the literature (*n*-heptane–methyl*cyclo*hexane,[1] *n*-heptane–toluene,[1] methyl*cyclo*hexane–toluene,[14] acetone–chloroform,[24] chloroform–benzene,[13] acetone–benzene [12]). The ternary equilibria of the system acetone–chloroform–benzene have been measured by Reinders and De-Minjers,[16] and Fig 2 has been plotted from this data. Data for the system heptane–methyl*cyclo*hexane–toluene were calculated from binary data and the few ternary points available in the literature,[1] by using the equations of Wohl,[23] and are plotted in Fig 3. The refractive index and density of the ternary mixtures were measured at 20° C and are plotted in Figs 4 and 5.

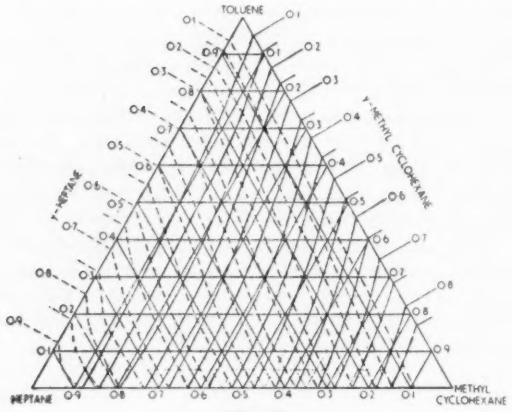

FIG 3

HEPTANE–METHYL*CYCLO*HEXANE–TOLUENE EQUILIBRIA

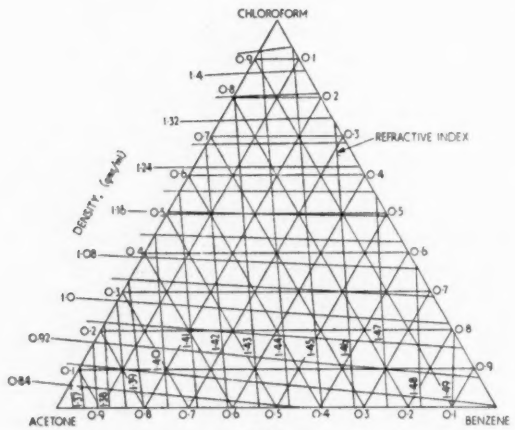

FIG 4

ACETONE–CHLOROFORM–BENZENE REFRACTIVE INDEX AND DENSITY LINES (AT 20° C)

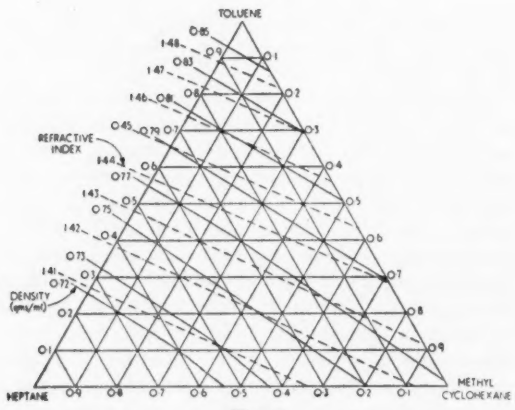

FIG 5

HEPTANE–METHYL*CYCLO*HEXANE–TOLUENE–REFRACTIVE INDEX AND DENSITY LINES

For the system heptane–methyl*cyclo*hexane–toluene, the lines of constant refractive index and density cut at an oblique angle, and therefore analysis is not as accurate as with the acetone–chloroform–benzene system, where the lines cross almost at right angles. Also the equilibrium data for the heptane–methyl*cyclo*hexane–toluene system were calculated and not measured, and therefore are less reliable than for the acetone–chloroform–benzene system. It is estimated that with the acetone–chloroform–benzene system the maximum error in each diagram is of the order of 1 mol per cent.

The effect of inaccuracies in these diagrams on the calculated value of H_{OG} is estimated later.

Many other properties of these systems have been measured or calculated.[15] They include the densities and viscosities of the binary liquid mixtures at temperatures from 20° C to the boiling point, the boiling points of the ternary mixtures, and the kinematic viscosities and vapour densities of the ternary liquid mixtures at the boiling point.

DISCUSSION OF THE EXPERIMENTAL RESULTS

Binary Mixtures

The performance of the column was first expressed in terms of the height of a transfer unit (based on overall vapour concentrations) defined by the equation

$$H_{OG} = H/\int_{y_B}^{y_T} \frac{dy}{y^* - y} \quad . \quad . \quad . \quad (1)$$

where y is the bulk vapour composition of the more volatile component (mol fraction);

y^* is the equilibrium value of the bulk liquid composition x (and for total reflux, $x = y$);

H is the total height of the wetted-wall section of the equipment;

T refers to the top of the column, and

B to the bottom of the column.

H_{OG} for the six binary mixtures making up the two ternary mixtures are plotted in Figs 6 and 7 against the mean bulk vapour concentration in the column. Since the maximum difference between y_T and y_B is of the order of 0·15 mol fraction, the arithmetic mean concentration is used.

Although the values have a different magnitude, the relationship between H_{OG} and composition has a similar form to that noticed by many other workers using packed and plate columns.[3–5,9,15,17–19,22] The performance becomes very small, or H_{OG} very large as the concentration tends to zero or unity, the position of the minimum value of H_{OG} varying from system to system. An interesting result is obtained with the acetone–chloroform mixture, which forms an azeotrope at 0·385 mol fraction acetone. A double

curve results, the split between the two regions occurring at the azeotropic composition.

Many reasons have been put forward for the apparent dependence of H_{OG} on the composition of binary mixtures undergoing separation by distillation.

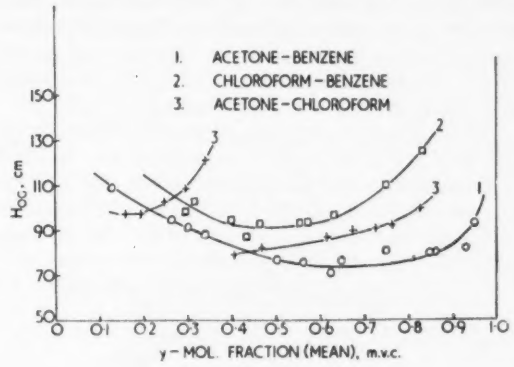

FIG 6

H_{OG} FOR BINARY MIXTURES

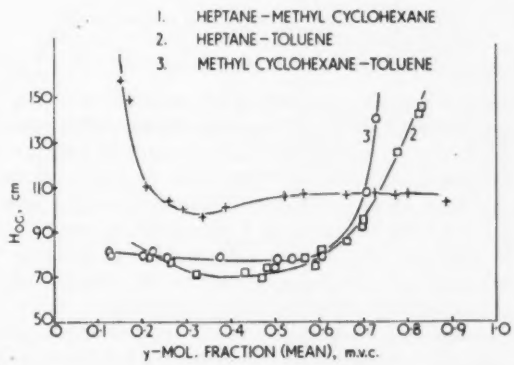

FIG 7

H_{OG} FOR BINARY MIXTURES

This matter has been discussed in detail elsewhere [17,19] and is not considered in this paper. The primary concern here is to find an empirical expression for the performance of the wetted-wall column which does not vary with composition. It is expected that any measure of the performance found to be suitable for the wetted-wall column will also be suitable for packed columns, and this will be confirmed.

The rate equation for mass transfer by distillation, from which H_{OG} is derived and defined as in equation (1), is

$$dN = G\,dy = K_G\,aS\,(y^* - y)\,dh \quad . \quad . \quad (2)$$

where dN is the amount of the m.v.c. transferred per unit time in height dh of the column;

G is the molal flow rate of the vapour;

a is the area of interface per unit volume of the column, and

S is the cross-sectional area of the column.

It can be shown that

$$H_{OG} = G/K_G\,aS \quad . \quad . \quad . \quad (3)$$

Now in practice H_{OG} is a function of y which has a minimum and becomes very large as y tends to 0 or 1. To counteract this variation it is necessary to multiply H_{OG} by another function which has a maximum and becomes zero as y tends to 0 or 1. One such function is $y(1-y)$, and therefore $H_{OG}y(1-y)$, which shall be written as H_e, may be independent of composition. By analogy with (3) can be put

$$H_e = G/K_e\,aS \quad . \quad . \quad . \quad . \quad (4)$$

so that

$$K_e = K_G/y(1-y) \quad . \quad . \quad . \quad (5)$$

and K_e, a modified transfer coefficient, may likewise be independent of composition. Substituting in (2), it is found that the rate equation becomes

$$dN = G\,dy = K_e\,aS\,(y^* - y)\,y(1-y)\,dh \quad (6)$$

The extra product term $y(1-y)$ can be accounted for in two ways. Either the mass transfer coefficient K_G is for some reason proportional directly or indirectly to $y(1-y)$ *e.g.* $y(1-y)$ may be proportional to the value of some physical property affecting the distillation process), or $(y^* - y)y(1-y)$ is more like the proper driving force for mass transfer in the column. Sawistowski [17] has inclined to the latter view, and he has shown that the term $y(1-y)$ arises when the rate of transfer across the interface can be specified by a first order rate equation.

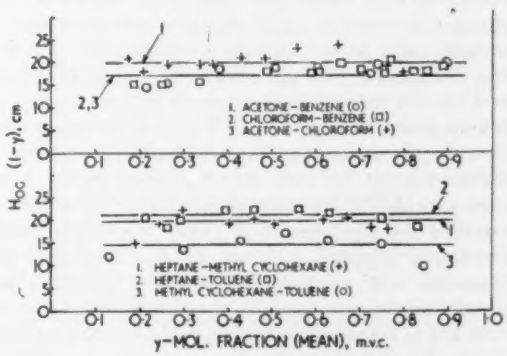
1. ACETONE - BENZENE (○)
2. CHLOROFORM - BENZENE (□)
3. ACETONE - CHLOROFORM (+)
1. HEPTANE - METHYL CYCLOHEXANE (+)
2. HEPTANE - TOLUENE (□)
3. METHYL CYCLOHEXANE - TOLUENE (○)
$H_{OG}(1-y)$, cm
y - MOL. FRACTION (MEAN), m.v.c.

FIG 8

H_e FOR BINARY MIXTURES

That H_e is much less dependent on concentration than H_{OG} is shown in Fig 8, where the results for the six binary mixtures tested are plotted. A graph of $y(1-y)$ versus y is a curve symmetrical about $y = 0{\cdot}5$, whereas the curve of H_{OG} versus y is not symmetrical, as may be seen in Figs 6 and 7. However, horizontal lines have been drawn in a mean position through points which are in addition scattered by experimental inaccuracies. The function does not account

well for the double curve obtained with the acetone–chloroform mixture which forms an azeotrope. There is also a tendency for the points to follow a line slightly convex upwards.

The same trend is shown by some careful measurements obtained by Sawistowski [17] from a packed column with and without re-distributors, separating heptane–toluene mixtures. These are plotted both as H_e and H_{OG} against the mean concentration in the column in Fig 9. It can be seen that H_e varies

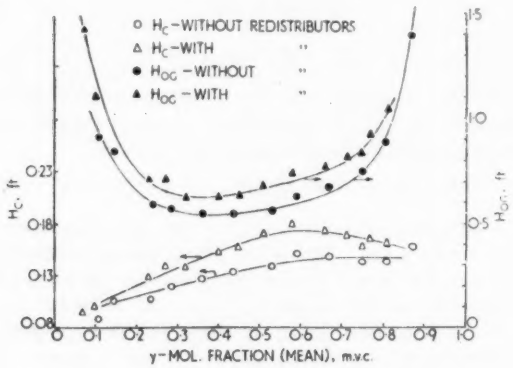

FIG 9

H_{OG} AND H_e FOR PACKED COLUMNS, HEPTANE–TOLUENE (AFTER SAWISTOWSKI [13])

over the concentration range $y = 0{\cdot}9$ to $0{\cdot}05$ only as much as H_{OG} varies between $0{\cdot}75$ and $0{\cdot}3$. H_e changes in value by ± 25 per cent and maintains a normal value as the mixture becomes pure, whereas H_{OG} changes by ± 50 per cent in the range examined and by very much more as y tends to 0 or 1. Sawistowski found that $y(1-y)^{1{\cdot}35}$ gave a better correlation for the system heptane–toluene. To specify a different index for each binary system would, however, complicate the correlation, and for the accuracy required for most design purposes the simple modification is adequate. Values of H_{OG} quoted in the literature and ascribed to particular packings are usually minimum values, *i.e.* they have been measured with the average concentration in the column between about 0·4 and 0·6 m.f. By assuming that H_e or $H_{OG}y(1-y)$ is constant, values of H_{OG} suitable when the mean concentration is more dilute can be estimated.

Ternary Mixtures

It is useful to plot the rectification lines of the column for each ternary system, and these are shown in Figs 10 and 11. The rectification lines follow the course of the concentration change in a column of infinite length. (They are plotted from the experimental results in the following way: in Fig 11 Y is the composition at the top of the wetted-wall column when X is the bottom composition and Z is the composition at the top of the column when Y is the bottom composition, and so on, the lines being for total reflux.) For a mixture with no azeotrope, the lines will always originate at the least volatile component (l.v.c.) apex and end at the most volatile

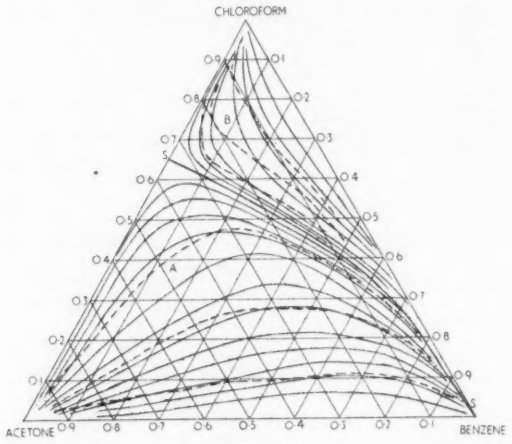

FIG 10

ACETONE–CHLOROFORM–BENZENE RECTIFICATION LINES

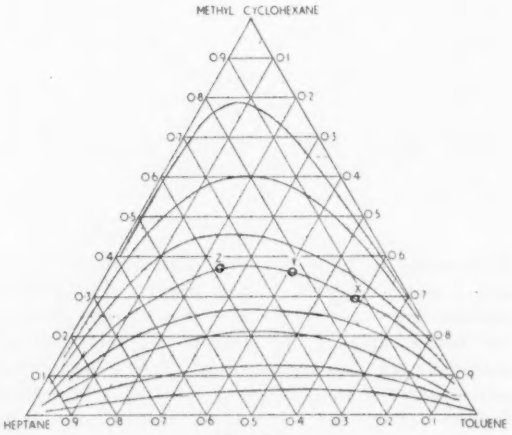

FIG 11

HEPTANE–METHYLCYCLOHEXANE–TOLUENE RECTIFICATION LINES

component (m.v.c.) apex. The acetone–chloroform–benzene mixture has a binary azeotrope of chloroform and acetone which is maximum boiling, but has a lower boiling point than benzene (l.v.c.). Thus, for this mixture, the diagram is split into two regions, A and B. Any mixture lying on the rectification line dividing these two regions (SS) will theoretically be

rectified to the azeotrope. Any mixture in region A will rectify to acetone and in region B to chloroform, all rectification lines starting at benzene. For a distillation at total reflux in a column with perfect plates the theoretical rectification lines are those dotted in Fig 10. The difference between the theoretical and experimental rectification lines is caused by a change in the efficiency of the wetted-wall column (H.E.T.P.) with composition.

The H_{OG} for the separation of a ternary mixture is more difficult to define and calculate than for a binary mixture. It is shown in Appendix 1 (*a*) that the value of H_{OG} calculated from a known separation of a binary mixture is bound to be the same whether the more or less volatile component is considered. But if equations are written equivalent to 1 for each component of a ternary mixture

$$H_{OG_1} = H / \int_{y_{B_1}}^{y_{T_1}} \frac{dy_1}{y^*_1 - y_1} \quad . \quad . \quad (7)$$

and similarly for each component, where we must have

$$y_1 + y_2 + y_3 = 1$$

and

$$y_1^* + y_2^* + y_3^* = 1_1$$

it does not follow that H_{OG} for each component is the same. Thus, for a binary mixture, y^*_1 is fixed in value by x_1 and through a material balance by y_1 alone. But for a ternary mixture y^*_1 is only fixed when two bulk compositions of the liquid or vapour are specified. It is shown in Appendix 1 (*b*) that, provided $y^* - y$ is properly the driving force controlling the rate of mass transfer, the value of H_{OG} will be the same for all three components. Otherwise the change in the bulk compositions of the components through the column will not necessarily be such that H_{OG} for each component works out to be the same. Here we are expecting H_{OG} to depend on composition, the implication being that $y^* - y$ is not the proper driving force, so the three H_{OG} values are not expected to be the same.

To determine the value of H_{OG} by equation (7) involves a tedious trial and error calculation. However, where the separation in the column is small it is permissible to write, as is proved in Appendix 2,

$$H_{OG_1} = \frac{(\Delta y_1)_{lm} H}{y_{1T} - y_{1B}} \quad . \quad . \quad (8)$$

where for total reflux

$$(\Delta y_1)_{lm} = \frac{(y^*_{1T} - y_{1T}) - (y^*_{1B} - y_{1B})}{\log_e \dfrac{(y^*_{1T} - y_{1T})}{(y^*_{1B} - y_{1B})}}$$

These equations have been used to calculate the values of H_{OG}, which in Figs 12 and 13 are plotted against the arithmetic mean vapour composition as before.

It should be noted that both the equilibrium data and the method of analysis is much less accurate for the heptane–methyl*cyclo*hexane–toluene system than for the acetone–chloroform–benzene system, and that Fig 13 shows only approximate values. In the case of Fig 12, since the concentration change through the column is small, there is most likely to be in Fig 2 an error of the same size and sign in y^*_{1T} and y^*_{1B}. This is also to be expected in Fig 4 and the net result of such errors on the value of H_{OG} will be very small. An error of E_1 in y^*_{1T} and an additional error of E_2 in

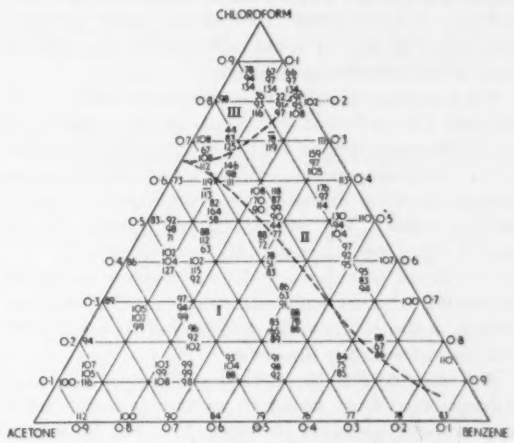

FIG 12

H_{OG} (CM) FOR TERNARY MIXTURES IN ORDER ACETONE, CHLOROFORM, BENZENE

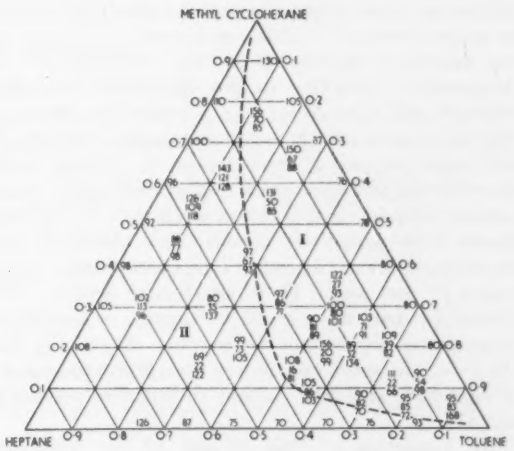

FIG 13

H_{OG} (CM) FOR TERNARY MIXTURES IN ORDER HEPTANE, METHYL*CYCLO*HEXANE, TOLUENE

y_{1T} (but not in y^*_{1B} or y_{1B}) leads to a total error in H_{OG} of approximately

$$\frac{E_1 + E_2}{y_{1T} - y_{1B}} \times 100 \text{ per cent}$$

High values of E_1 and E_2 are about 1 mol per cent, and $y_{1T} - y_{1B}$ is about 15 mol per cent, giving a total error in H_{OG} of a maximum of 15 per cent, an error of this size being unlikely.

For a ternary mixture it is possible to differentiate between two different conditions in the column, for one of the components, that of intermediate volatility (i.v.c.) or boiling point, can be transferred by a net amount in either direction, *i.e.* from liquid to vapour or vice versa. The other two components can be moved by a net amount only in one direction (*i.e.* m.v.c. liquid to vapour and l.v.c. vapour to liquid). By noting whether its concentration increases or decreases in the column, the direction of transfer of the l.v.c. is immediately apparent.

Referring to Fig 13, methyl*cyclo*hexane, the i.v.c. is transferred from liquid to vapour in region I and from vapour to liquid in region II. Fig 12 is complicated by the maximum boiling binary azeotrope of chloroform and acetone (the azeotrope having a lower boiling point than benzene). In region A, *i.e.* on the acetone side of the rectification line joining benzene and the azeotrope (Fig 10), the rectification is between benzene and acetone, the azeotrope acting as an intermediate volatile component. In region B the azeotrope likewise acts like a component of intermediate volatility in the separation between benzene and chloroform. As a result the diagram (Fig 12) divides into three regions: region I, in which only acetone passes from liquid to vapour, and therefore the azeotrope or i.v.c. effectively passes from vapour to liquid; region III, in which only chloroform passes from liquid to vapour, and therefore the azeotrope or i.v.c. passes from vapour to liquid, as in region I; and region II, in which both acetone and chloroform pass from liquid to vapour, or the azeotrope passes from liquid to vapour. So, in Fig 12, the i.v.c., the azeotrope, moves from liquid to vapour in region II, and from vapour to liquid in regions I and III.

By inspection of Figs 12 and 13 the following behaviour can be noticed:

(1) when two components are transferred from liquid to vapour the H_{OG} is higher for the more volatile of the two components;

(2) when two components are transferred from vapour to liquid, the H_{OG} is higher for the less volatile of the two components; and

(3) the H_{OG} of that component being transferred alone in either direction lies between those of the other two components.

However, there appears to be no simple relationship between the values of H_{OG} and the mean concentration of the ternary mixture in the column, as has been found for binary mixtures. Nord [11] has measured the separation of a ternary mixture by a plate column. It can be seen from his work that the plate efficiency of each component changes with composition in a manner similar to that of $1/H_{OG}$ obtained in this work.

When allowance is made for the dependence of H_{OG} for each component on concentration, proper calculation of the change in composition through the column is difficult. Only when it can be assumed that H_{OG} is the same for all three components and independent of concentration does the calculation simplify appreciably. It is unlikely that H_{OG} data would in any case be available for the proper calculation. In practice, the only data on efficiency would be a single figure for H_{OG} or H.E.T.P. for a particular packing, measured near its minimum value for a binary mixture. The question therefore arises: knowing H_{OG} near the minimum value for binary systems, what value should be used for ternary systems? It should be remembered that in a column separating a ternary feed mixture continuously, the length of the rectifying section will usually be determined by the separation required between the m.v.c. and the i.v.c. (since the i.v.c. will often be specified at a low value in the top product and the l.v.c. will be in negligible amount). In this case the m.v.c. alone will be transferred from liquid to vapour, whilst the other two components are transferred from vapour to liquid. The values of H_{OG} measured in this work then show that the important separation is between those components having the lowest and the intermediate value of H_{OG} respectively. It will most often be found that this is also true for the stripping section of the column. The single high value is possessed by that component which is not of importance in the separation. In Figs 12 and 13 it can be seen that the average of the two lowest values of H_{OG} is of the same order as the average value found for binary mixtures, and therefore in practice no considerable error will be introduced by assuming that the value of H_{OG} measured for a binary system can be used for a ternary system. This argument cannot be applied to extractive distillation, where one of the components is very much less volatile than the other two, and the efficiency is likely to be low for all three components.

ACKNOWLEDGMENTS

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APPENDIX I

(*a*) *Binary Mixtures*

The rate equation for a two-component mixture can be written for each component as

$$G\,dy_1 = K_{Ga1}S\,(y^*_1 - y_1)dh \quad . \quad . \quad (1.1)$$

$$G\,dy_2 = K_{Ga2}S\,(y^*_2 - y_2)dh \quad . \quad . \quad (1.2)$$

where for the moment we admit the possibility that

$$K_{Ga1} \neq K_{Ga2}$$

Also we must have

$$y_1 + y_2 = 1 \quad . \quad . \quad . \quad . \quad . \quad (1.3)$$

or

$$dy_1 + dy_2 = 0 \quad . \quad . \quad . \quad . \quad (1.4)$$

and

$$y^*_1 + y^*_2 = 1 \quad . \quad . \quad . \quad . \quad (1.5)$$

Substitute (1.3), (1.4), and (1.5) into (1.2) and

$$G\,dy_1 = K_{Ga2}S\,(y^*_1 - y_1)dh$$

So that by (1.1)

$$K_{Ga1} = K_{Ga2} \quad . \quad . \quad . \quad . \quad . \quad (1.6)$$

Integrate (1.1) and (1.2),

$$N_{OG1} = \int_{y_1B}^{y_1T} \frac{dy_1}{y^*_1 - y_1} = \frac{K_{Ga1}SH}{G} \quad . \quad . \quad (1.7)$$

and

$$N_{OG2} = \int_{y_2B}^{y_2T} \frac{dy_2}{y^*_2 - y_2} = \frac{K_{Ga2}SH}{G} \quad . \quad . \quad (1.8)$$

As $K_{Ga1} = K_{Ga2}$, then $N_{OG1} = N_{OG2}$, and it follows that the two integrals should have the same value. Provided that K_{Ga1} and K_{Ga2} are constant and independent of concentration, the equality of the two integrals is automatically ensured by equations (1.1) and (1.2), which then require that

$$\frac{dy_1}{y^*_1 - y_1} = \frac{dy_2}{y^*_2 - y_2} \quad . \quad . \quad . \quad (1.9)$$

If equations (1.1) and (1.2) were not obeyed, the two integrals would not necessarily be equal, except for the fact that for a binary mixture direct substitution of y^*_2 and y_2 by y^*_1 and y_1 from equations (1.3) and (1.5) also ensures that (1.9) is obeyed. This means that for a binary mixture H_{OG1} and H_{OG2} always have the same value for the same separation whether equations (1.1) and (1.2) are obeyed or not.

(*b*) *Ternary Mixtures*

The rate equations for a ternary mixture can be written for each component as

$$G\,dy_1 = K_{Ga1}S\,(y^*_1 - y_1)\,dh \quad . \quad . \quad (2.1)$$

$$G\,dy_2 = K_{Ga2}S\,(y^*_2 - y_2)\,dh \quad . \quad . \quad (2.2)$$

$$G\,dy_3 = K_{Ga3}S\,(y^*_3 - y_3)\,dh \quad . \quad . \quad (2.3)$$

Also

$$y_1 + y_2 + y_3 = 1 \quad . \quad . \quad . \quad (2.4)$$

$$dy_1 + dy_2 + dy_3 = 0 \quad . \quad . \quad . \quad (2.5)$$

$$y^*_1 + y^*_2 + y^*_3 = 1 \quad . \quad . \quad . \quad (2.6)$$

Substituting (2.4), (2.5), and (2.6) into (2.1),

$$-G(dy_2 + dy_3) = -K_{Ga1}S((y^*_2 - y_2) + (y^*_3 - y_3))\,dh$$

Eliminating $y^*_2 - y_2$ and $y^*_3 - y_3$ from (2.2) and (2.3) and simplifying

$$\frac{dy_2}{dy_3} = -\frac{K_{Ga3} - K_{Ga1}}{K_{Ga2} - K_{Ga1}} \cdot \frac{K_{Ga2}}{K_{Ga3}}$$

or, since

$$K_{Ga} = G/H_{OG}S,$$

$$\frac{dy_2}{dy_3} = \frac{H_{OG3} - H_{OG1}}{H_{OG1} - H_{OG2}} \quad . \quad . \quad . \quad (2.7)$$

It can be shown in the same way that

$$\frac{dy_1}{dy_3} = \frac{H_{OG3} - H_{OG2}}{H_{OG2} - H_{OG1}} \quad . \quad . \quad . \quad (2.8)$$

Adding (2.7) and (2.8),

$$\frac{dy_1 + dy_2}{dy_3} = -1 = \frac{H_{OG3} - H_{OG1} + H_{OG3} - H_{OG2}}{H_{OG2} - H_{OG1}}$$

or

$$H_{OG3} = H_{OG1}$$

Also it can be shown that

$$H_{OG3} = H_{OG2}$$

so that

$$K_{Ga1} = K_{Ga2} = K_{Ga3}$$

as for binary mixtures.
This has been proved by other workers in different ways.[19, 20]
We integrate equations (2.1), (2.2), and (2.3) to give

$$N_{OGi} = \int_{y_{iB}}^{y_{iT}} \frac{dy_i}{y^*_i - y_i} = \frac{K_{Gai}SH}{G}$$

$$(i = 1, 2, \text{and } 3)$$

As before the three integrals should be the same, since the three mass transfer coefficients are the same. Provided that equations (2.1), (2.2), and (2.3) are exactly obeyed this is ensured. However, if (2.1), (2.2), and (2.3) are not obeyed, as is expected in this work, then the three integrals will not necessarily be equal. Unlike the case of binary mixtures, equations (2.4), (2.5), and (2.6) do not ensure the equality of the integrals in this case. It is not likely therefore that the values of N_{OG} or H_{OG} for each component calculated from the experimental results will be equal.

M

APPENDIX II

Log Mean Concentration Difference

We desire to find the number of transfer units for a ternary mixture when the concentration change of all three components throughout the column is small.

For component 1

$$N_{OG_1} = \int_{y_{B_1}}^{y_{T_1}} \frac{dy_1}{y^*_1 - y_1} \quad . \quad . \quad (3.1)$$

This can only be determined if we have y^*_1 as a function of y_1. But y^*_1 is a function not only of x_1 (and hence y_1) but also of x_2 or x_3, the liquid compositions of the other components. However, when the concentration change is small the effect of a change of x_2 (say) on the equilibrium value y^*_1 can be neglected. Also we can assume that

$$y^*_1 = m_1 x_1 + c_1 \quad . \quad . \quad . \quad (3.2)$$

where m_1 is the slope of the equilibrium curve at x_1 in the direction of the rectification line. The operating lines give

$$x_1 = G/_{L}y_1 - D/_{L}x_{D_1} \quad . \quad . \quad . \quad (3.3)$$

where L and D are the liquid and product molal flow rates and x_{D_1} is the product composition of component 1.

Therefore

$$y^*_1 = a_1 y_1 + b_1 \quad . \quad . \quad . \quad . \quad (3.4)$$

where

$$a_1 = m_1{}^{G}/_{L} \text{ and } b_1 = c_1 - m_1{}^{D}/_{L}x_{D_1}$$

Substituting for y^*_1 in 3.1 and integrating

$$N_{OG_1} = \frac{1}{a_1 - 1} \log_e \frac{(a_1 y_{1T} - y_{T_1} + b_1)}{(a_1 y_{1B} - y_{1B} + b_1)} \quad . \quad (3.5)$$

But

$$m_1 = \frac{y_1{}^*{}_T - y^*_{1B}}{y_{1T} - y_{1B}}$$

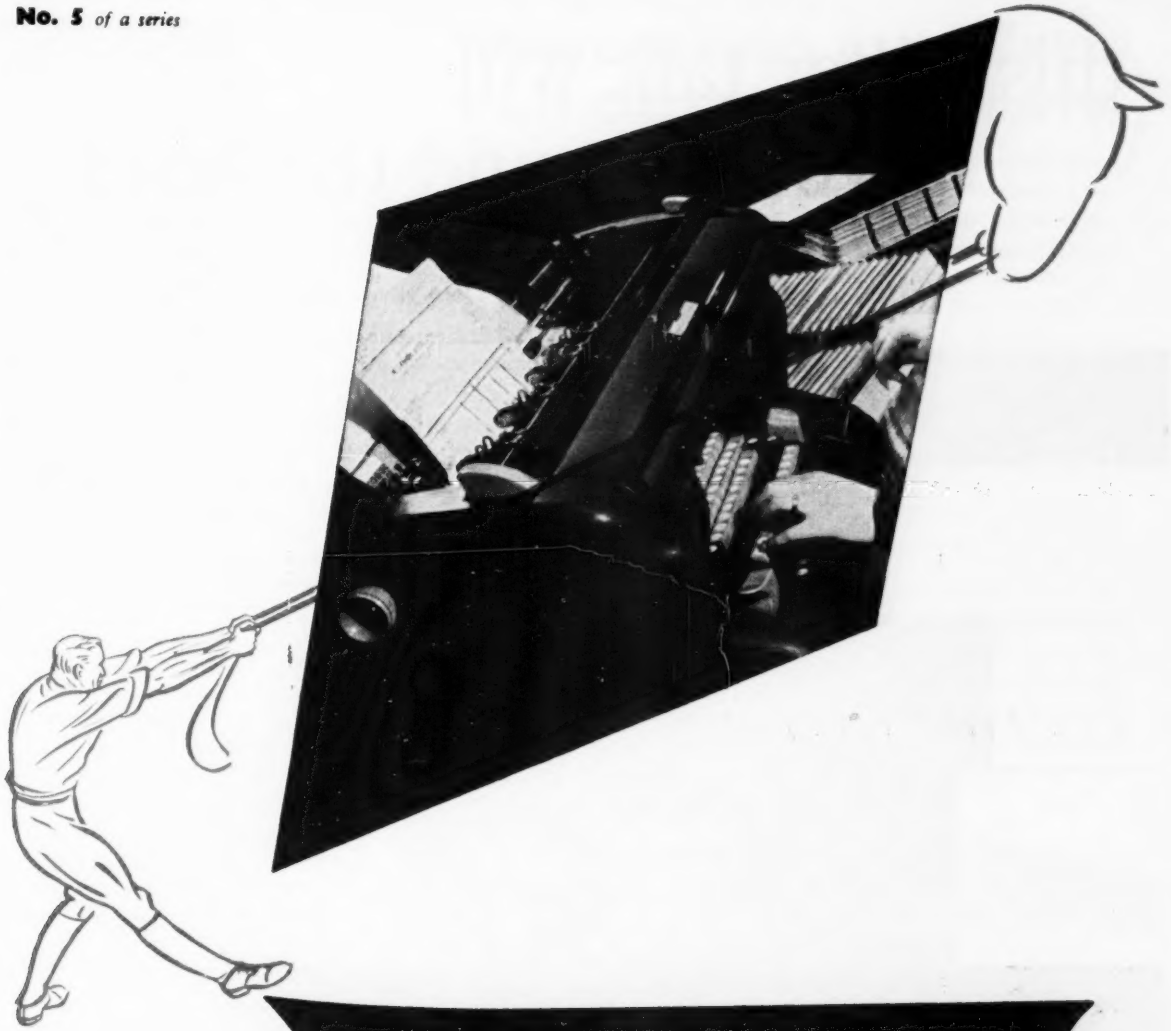
So, substituting for a_1 and $a_1 y_1 + b_1$,

$$N_{OG_1} = \frac{y_{1T} - y_{1B}}{(\Delta y_1)_{lm}} \quad . \quad . \quad . \quad (3.6)$$

where

$$(\Delta y_1)_{lm} = \frac{\left(\frac{G}{L} y^*_{1T} - y_{1T}\right) - \left(\frac{G}{L} y^*_{1B} - y_{1B}\right)}{\log_e \frac{(y^*_{1T} - y_{1T})}{(y^*_{1B} - y^*_{1B})}} \quad (3.7)$$

No. 5 *of a series*



COST CONTROL

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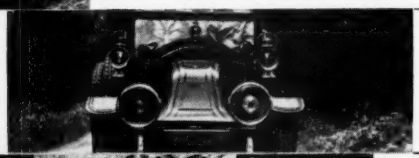
TAS/PS.473

a

this Filter talk will drive me round the bend!

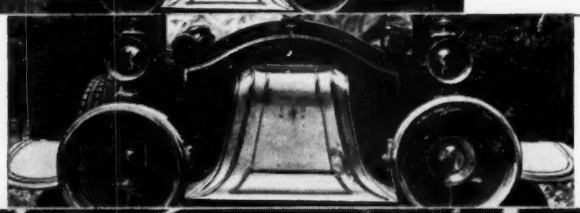
Sorry, old fruit. I was only trying to be helpful.

Helpful! Here am I practising for the only real sporting event of the year and all you can talk about is some wretched little gadget on one of your blasted hairyplanes. Can't you see I need to concentrate?

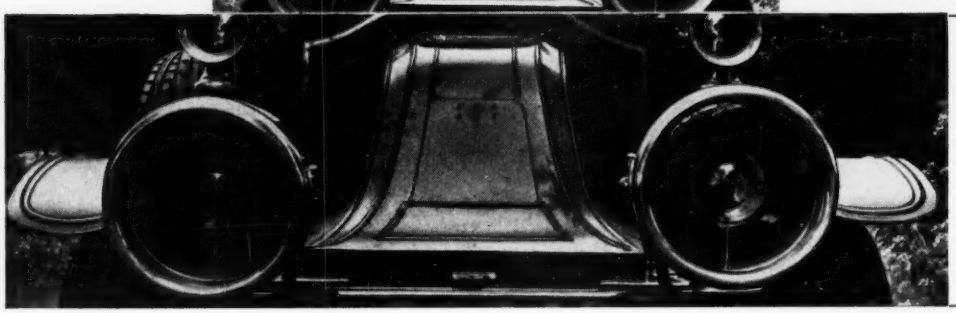


It's not a little gadget and they'd never put it on a plane—it's bigger than this Renault. They put it in the line between the storage and aircraft tanks to make sure the plane gets clean, water-free fuel.

That's the trouble with your infantile modern engines—they have to be fed on strained foods or they get indigestion. Now look at Dotty . . .



Exactly. Do you really think she enjoys having that steam pouring through her exhaust? Now if you took a Simmonds Fram Separator Filter in tow you could have 100% water separation and complete filtration of solids down to 5 microns.



It's tempting, very tempting . . . but it wouldn't be fair on the other competitors. Now d'you mind if we stop a minute . . . I think I really will have to get the rest of that bird's nest out of the tank.

the point of the argument... **FRAM SEPARATOR FILTERS** for clean water-free fuel

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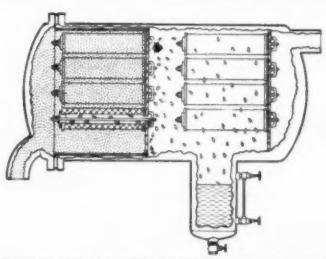
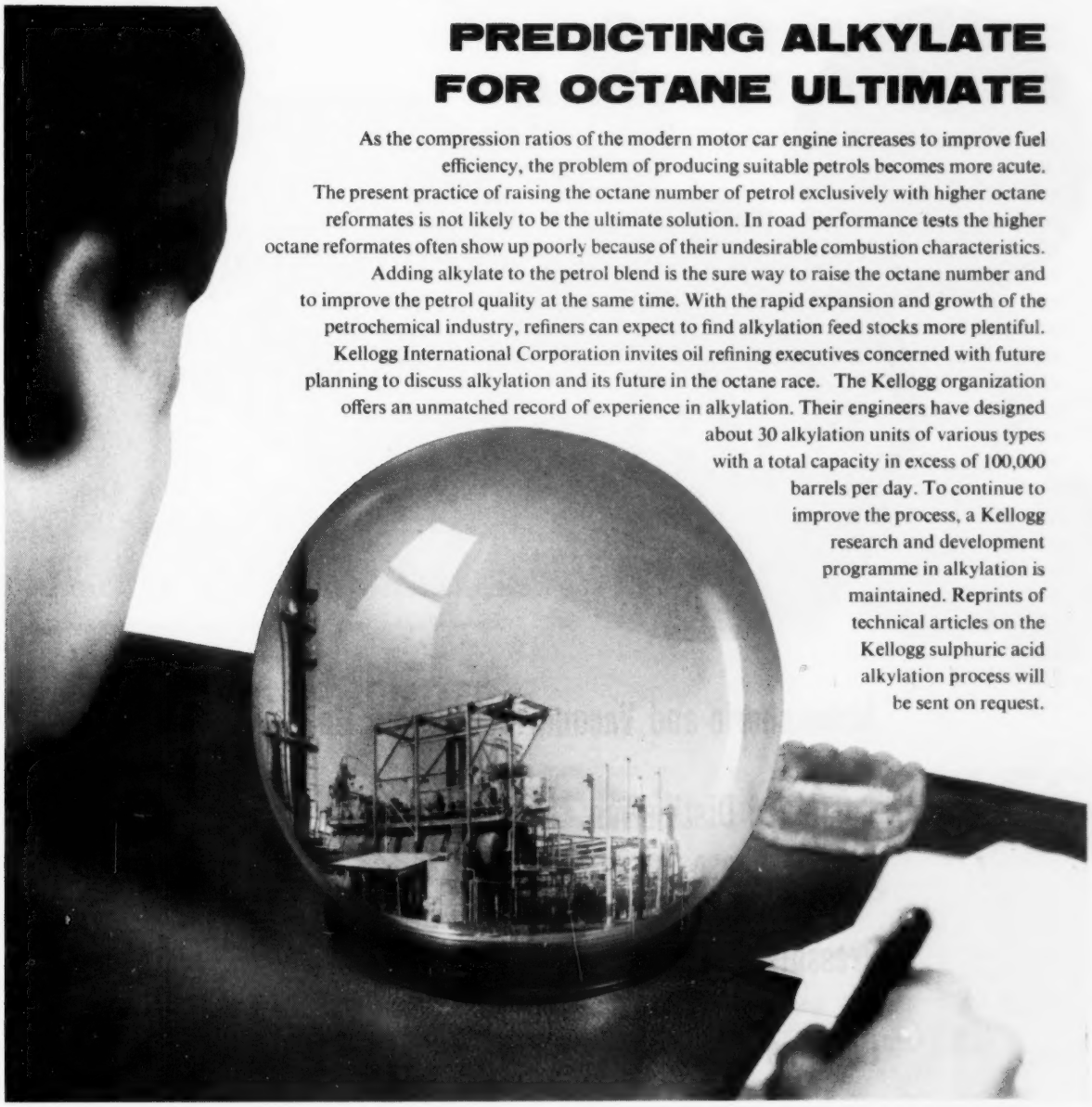


CRC 6WS

PREDICTING ALKYLATE FOR OCTANE ULTIMATE

As the compression ratios of the modern motor car engine increases to improve fuel efficiency, the problem of producing suitable petrols becomes more acute. The present practice of raising the octane number of petrol exclusively with higher octane reformates is not likely to be the ultimate solution. In road performance tests the higher octane reformates often show up poorly because of their undesirable combustion characteristics. Adding alkylate to the petrol blend is the sure way to raise the octane number and to improve the petrol quality at the same time. With the rapid expansion and growth of the petrochemical industry, refiners can expect to find alkylation feed stocks more plentiful. Kellogg International Corporation invites oil refining executives concerned with future planning to discuss alkylation and its future in the octane race. The Kellogg organization offers an unmatched record of experience in alkylation. Their engineers have designed about 30 alkylation units of various types with a total capacity in excess of 100,000 barrels per day. To continue to improve the process, a Kellogg research and development programme in alkylation is maintained. Reprints of technical articles on the Kellogg sulphuric acid alkylation process will be sent on request.



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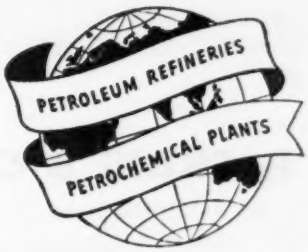

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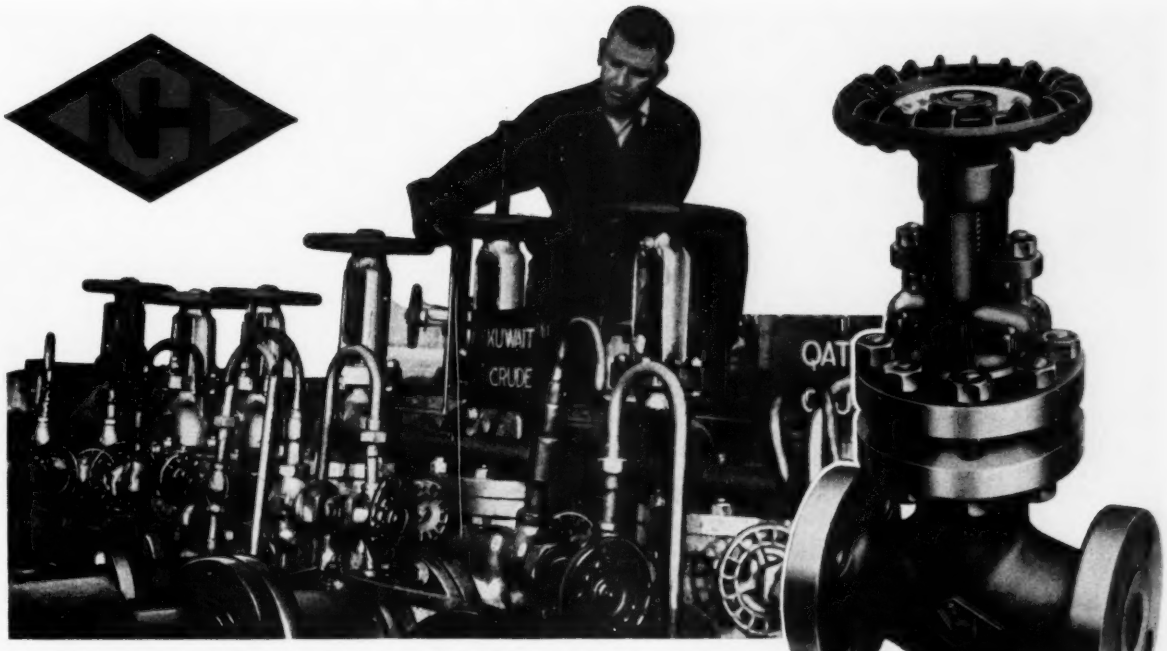

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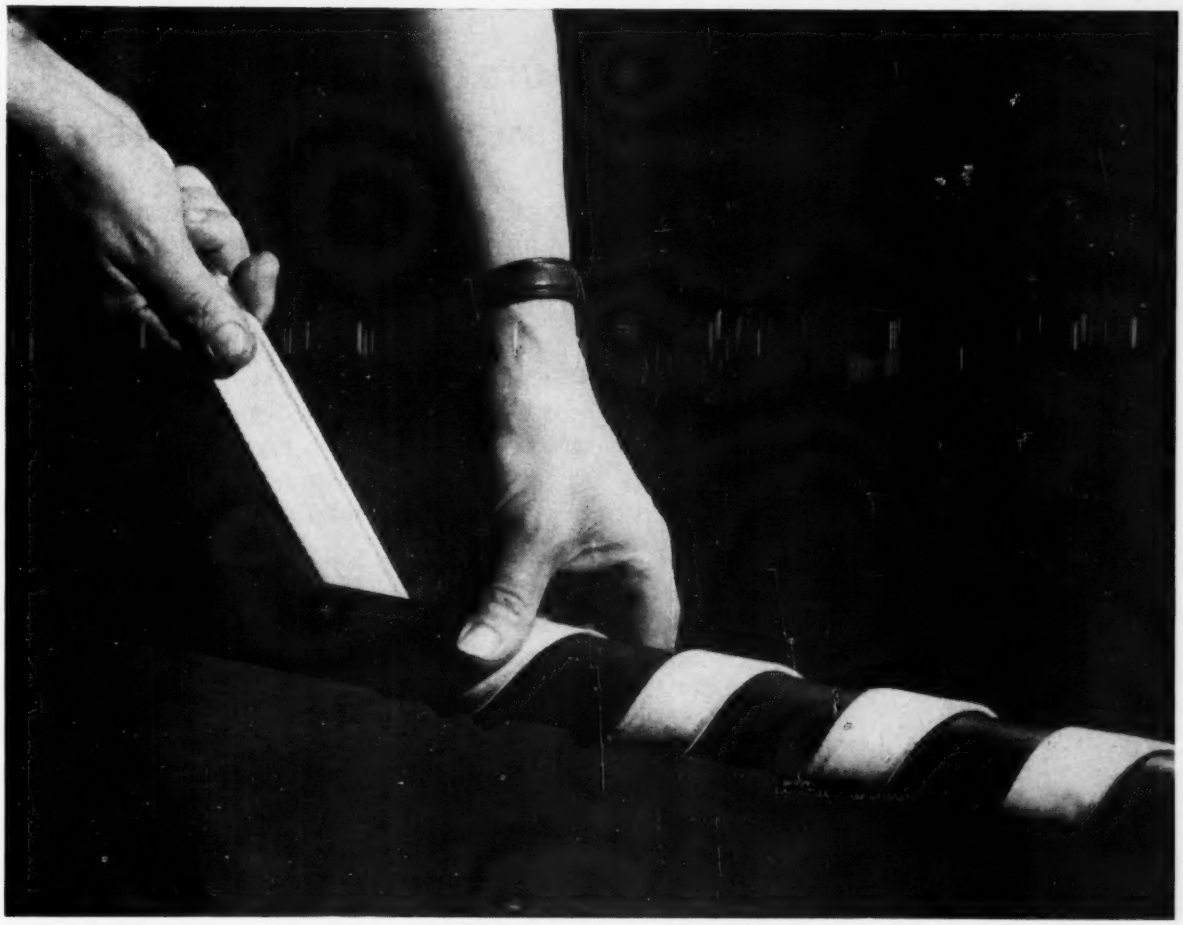

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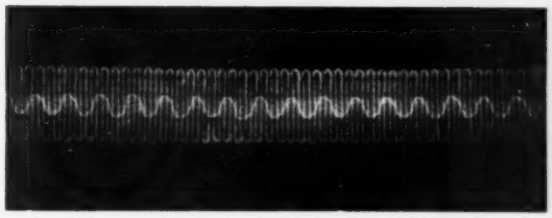

Illustrated above is an X-Ray photograph of a typical tape section.

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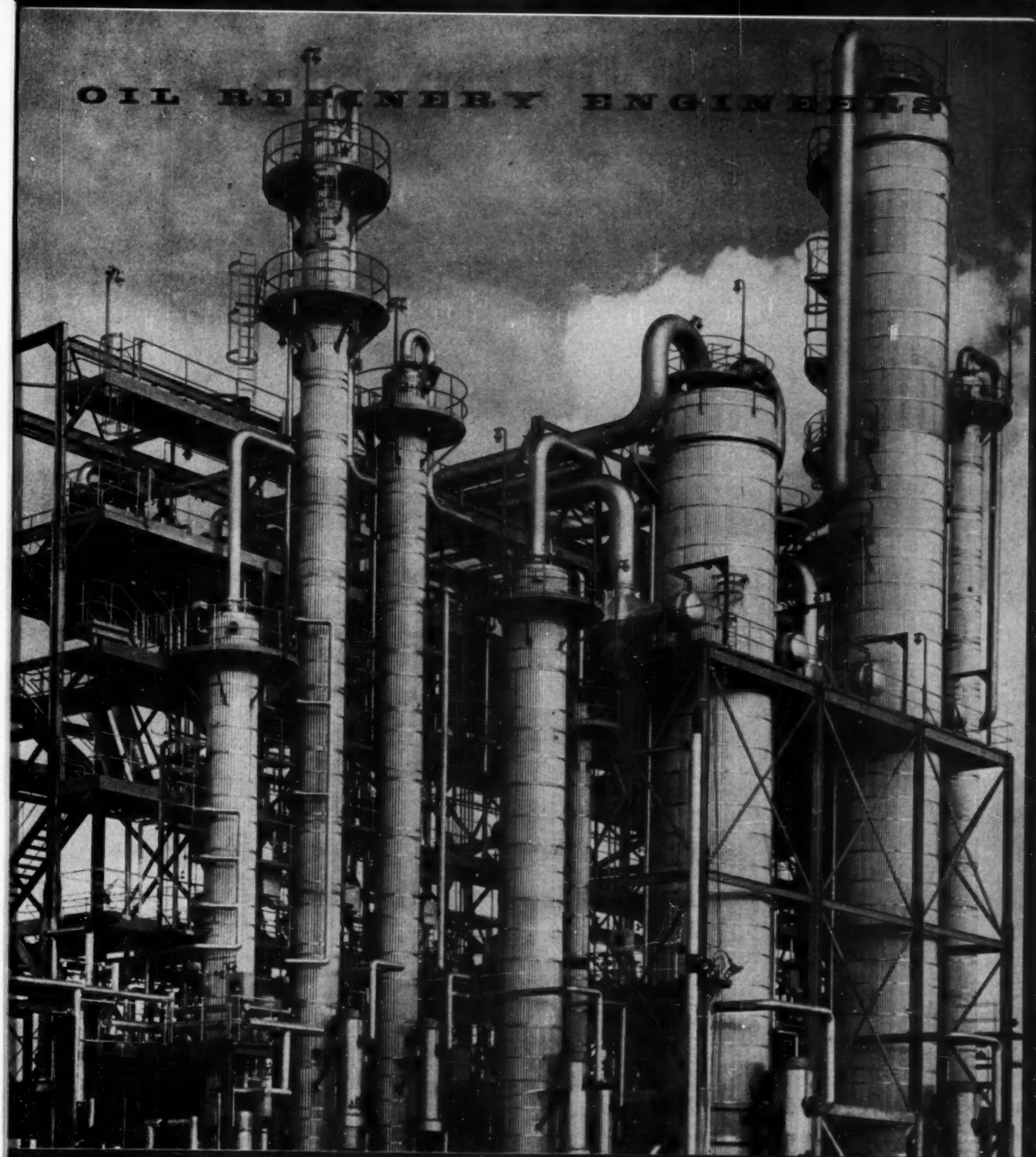

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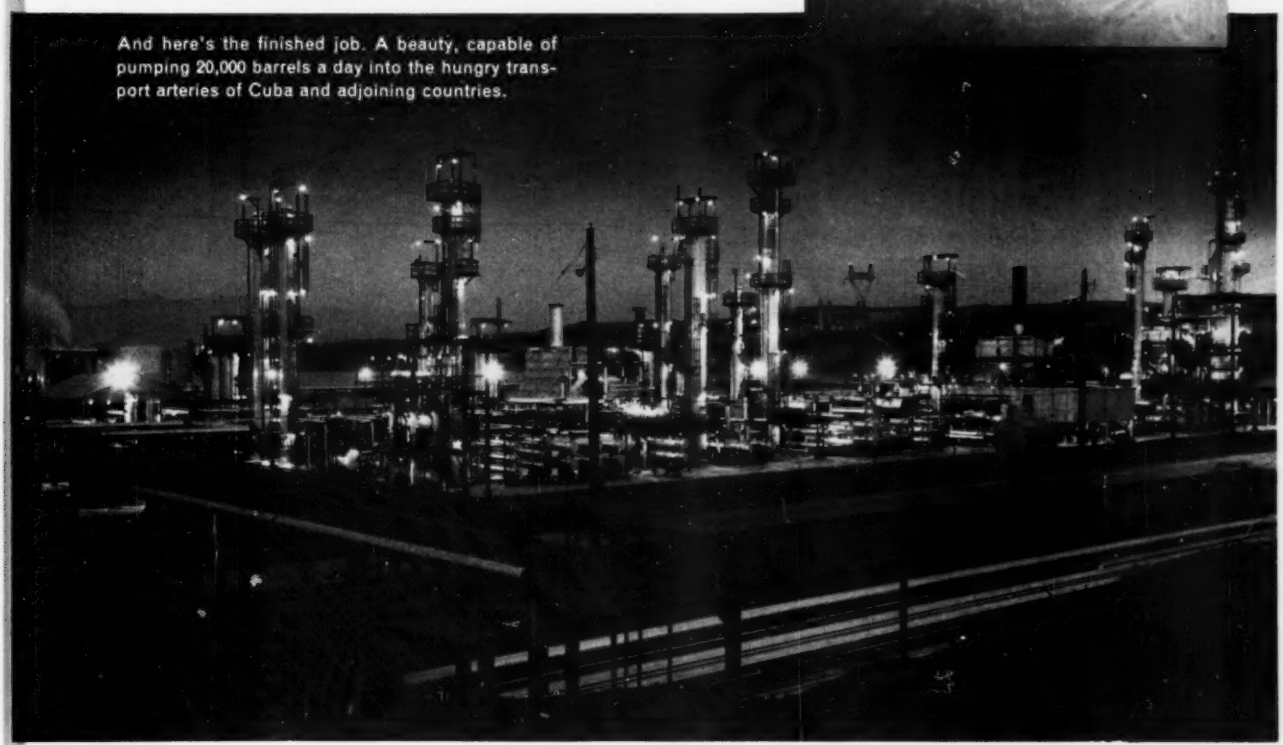

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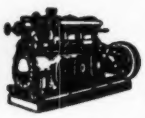

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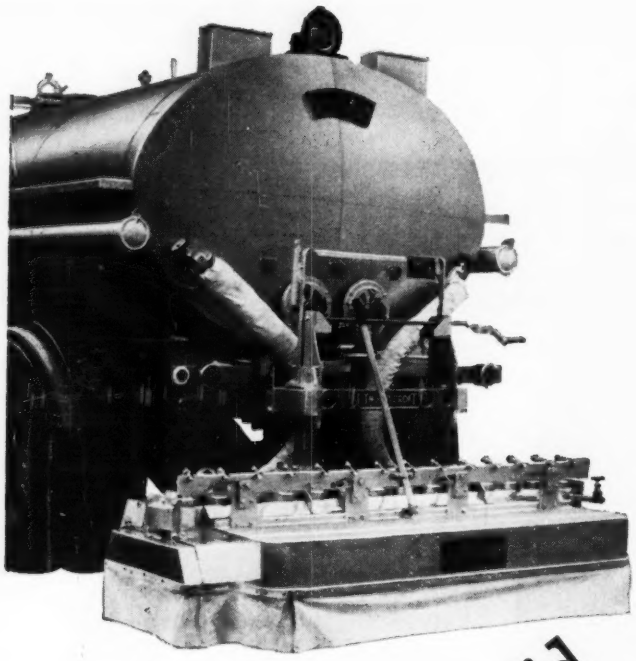

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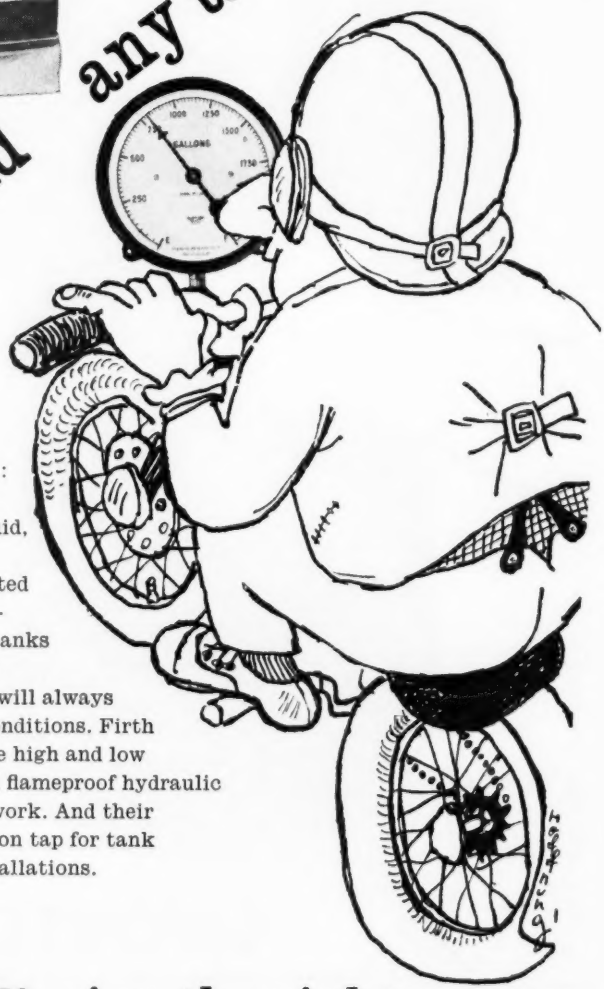

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